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Recovery Potential Assessment for Eastern Cape Breton Atlantic Salmon (*Salmo salar*): Population Viability Analyses

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Eastern Cape Breton (ECB) Designatable Unit (DU) of Atlantic Salmon was assessed as "Endangered" by the Committee on the Status of Endangered Wildlife in Canada in 2010. This document, prepared in support of a recovery potential assessment for this DU, contains information about the dynamics and viability of salmon in two of the 46 rivers thought to support ECB salmon populations. These two populations, found in the Middle and Baddeck rivers, are the only two ECB populations with sufficient data to evaluate population dynamics, and data for these populations, particularly age composition data, are limited. A forward projecting population dynamics model was developed that is specific to the types of data available for these populations. Output from the model includes estimates of smolt age and sea age composition, asymptotic recruitment levels, maximum lifetime reproductive rates, and equilibrium population sizes.

Despite these populations being in close geographic proximity, and subject to uncertainty in the results, model output indicates that the dynamics of these populations differ. Equilibrium calculations, based on current estimates of stage-specific mortality and maturity rates, suggest that abundance should tend toward 50% of the conservation requirement of the respective river. However, the estimated maximum lifetime reproductive rate (the maximum number of spawners produced by a spawner throughout its life at very low abundance – a key indicator of extinction risk) for the Middle population is double that of the Baddeck population (values of 3.22 and 1.61 spawners/ spawner, respectively). Relative to populations in the Southern Upland and inner Bay of Fundy Atlantic Salmon DUs, these dynamics indicate a lower risk of extirpation for these two ECB populations. Trends in the recruitment deviates from the model are suggestive that productivity in the Middle population has not changed during the last 30 years, whereas the productivity of Baddeck population may have declined slowly during this time.

Population viability analyses based on this model indicate that, under current conditions, there is a low probability of extinction or of meeting recovery targets for these two populations if conditions remain unchanged.

There are differences in life history strategies among salmon populations in eastern Cape Breton; one of the most notable is the difference in the proportion of salmon maturing after one winter at sea as observed for Cape Breton Highland populations and for the populations to the southeast. Given these differences, inferences cannot be made about the dynamics and viability of other ECB populations based on the dynamics of populations in the Middle and Baddeck rivers.

Évaluation du potentiel de rétablissement (EPR) du saumon de l'Atlantique (*Salmo salar*) de l'est du Cap-Breton : Analyses de la viabilité de la population

RÉSUMÉ

En 2010, le Comité sur la situation des espèces en péril au Canada a désigné l'unité désignable du saumon de l'Atlantique de l'est du Cap-Breton comme une espèce en voie de disparition. Le présent document a été préparé à l'appui d'une évaluation du potentiel de rétablissement de cette unité désignable et contient des renseignements sur la dynamique et la viabilité du saumon dans deux des 46 rivières que l'on pense soutenir les populations de saumon de l'est du Cap-Breton. Ces deux populations, qui se trouvent dans les rivières Middle et Baddeck, sont les deux seules populations de l'est du Cap-Breton sur lesquelles les données sont suffisantes pour évaluer la dynamique de la population. Toutefois, les données sur ces populations, en particulier sur leur composition selon l'âge, sont limitées. Un modèle de projection prospective de la dynamique des populations propre aux types de données disponibles pour ces populations a été élaboré. Les données du modèle comprennent entre autres les estimations de la composition selon l'âge (âge des saumoneaux, nombre d'années passées en mer), les niveaux de recrutement asymptotiques, les taux de reproduction maximale à vie et la taille à l'équilibre de la population.

Malgré la proximité géographique de ces populations, et sous réserve des incertitudes des résultats, les données du modèle indiquent que les dynamiques de ces populations diffèrent. Les calculs de l'équilibre, basés sur les estimations actuelles des taux de mortalité et de maturité selon le stade, laissent entendre que l'abondance devrait se rapprocher respectivement de 50 % des exigences de conservation dans les rivières. Cependant, le taux de reproduction maximal à vie estimé (nombre maximal de reproducteurs produits par un reproducteur au cours de sa vie tout entière à très faible abondance – indicateur clé du risque d'extinction) pour la population de la rivière Middle est deux fois plus élevé que celui de la population de la rivière Baddeck (3,22 et 1,61 reproducteurs par reproducteur respectivement). Ces dynamiques indiquent que le risque de disparition de ces deux populations de l'est du Cap-Breton est plus faible par rapport aux populations des unités désignables du saumon de l'Atlantique des hautes terres du Sud et de l'intérieur de la baie de Fundy. Les tendances dans les écarts de recrutement par rapport au modèle révèlent que la productivité de la population de la rivière Middle n'a pas changé au cours des 30 dernières années, tandis que la productivité de la population de la rivière Baddeck pourrait avoir diminué lentement pendant cette même période.

Les analyses de la viabilité de la population d'après ce modèle indiquent que, dans des conditions semblables aux conditions actuelles, la probabilité d'extinction de ces deux populations est faible tout comme la probabilité d'atteindre les objectifs de rétablissement.

Il existe des différences au niveau du cycle vital des populations de saumon dans l'est du Cap-Breton. L'une des plus importantes est la proportion de saumons qui atteignent la maturité après avoir passé un hiver en mer, comme le montrent les observations des populations de saumon des hautes terres du Cap-Breton et du sud-est. Compte tenu de ces différences, il n'est pas possible de tirer des conclusions au sujet de la dynamique et de la viabilité des autres populations de l'est du Cap-Breton en se fondant sur la dynamique des populations dans les rivières Middle et Baddeck.

1.0 INTRODUCTION

The Eastern Cape Breton (ECB) Designatable Unit (DU) of Atlantic Salmon includes all anadromous salmon populations reproducing in ECB rivers draining into the Bras d'Or Lakes and Atlantic Ocean from the northern tip of Cape Breton to the Canso Causeway (Figure 1 in Gibson et al. (2014)). It is one of 16 Atlantic Salmon DUs whose conservation status was assessed by the Committee on the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2010), and it is one of the five DUs whose status was determined to be "Endangered" during that assessment.

This research document is one of four research documents prepared in support of a recovery potential assessment (RPA) for the ECB DU of Atlantic Salmon. An RPA is intended to provide a compilation of information and scientific advice required to meet the various requirements of the *Species at Risk Act* following a designation of "Endangered" or "Threatened" for a DU by COSEWIC.

All rivers containing ECB salmon are located within Salmon Fishing Area (SFA) 19, which is an area used by the Fisheries and Oceans Canada (DFO) for salmon fisheries management and assessment purposes. There are 46 ECB rivers that were identified as salmon rivers during this RPA (Gibson et al. 2014), although salmon likely use most accessible habitat, or did so in the past. This research document is focused on information about life history parameter values, population dynamics and population viability for populations in two of these rivers.

The Terms of Reference developed to guide this RPA process contained a set of 27 objectives. The specific objectives addressed within this document are:

Assess Current/Recent Species Status

3. Estimate, to the extent that information allows, the current or recent life-history parameters (total mortality, natural mortality, fecundity, maturity, recruitment, etc.) or reasonable surrogates; and associated uncertainties for all parameters (in part – see also Levy and Gibson 2014).

5. Project expected population trajectories over three generations (or other biologically reasonable time), and trajectories over time to the recovery target (if possible to achieve), given current parameters for population dynamics and associated uncertainties using DFO guidelines on long-term projections (Shelton et al. 2007).

Scope for Management to Facilitate Recovery

17. Assess the probability that the recovery targets can be achieved under current rates of parameters for population dynamics, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

Scenarios for Mitigation and Alternative to Activities

25. Project expected population trajectory (and uncertainties) over three generations (or other biologically reasonable time), and to the time of reaching recovery targets when recovery is feasible; given mortality rates and productivities associated with specific scenarios identified for exploration (as above). Include scenarios which provide as high a probability of survivorship and recovery as possible for biologically realistic parameter values.

26. Recommend parameter values for population productivity and starting mortality rates, and where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts of listing the species.

Allowable Harm Assessment

27. Evaluate maximum human-induced mortality which the species can sustain and not jeopardize survival or recovery of the species.

Three other research documents produced in support of this RPA provide information about: genetic diversity and population structuring (O'Reilly et al. 2013), abundance, trends and recovery targets (Levy and Gibson 2014), and habitat use and threats to populations (Gibson et al. 2014). Further information about the assessments and status of ECB Atlantic Salmon populations can be found in: DFO (2012), Gibson and Bowlby (2009) and Robichaud-LeBlanc and Amiro (2004).

2.0 ESTIMATION OF LIFE HISTORY PARAMETER VALUES

2.1 LIFE CYCLE

Eastern Cape Breton Atlantic Salmon are anadromous fish, meaning that while they are obligated to reproduce in fresh water, most spend part of their lives in the ocean to feed and grow. They are iterparous, meaning that they can spawn several times before they die. After spawning for the first time, some individuals may spawn again in consecutive years, while others may spawn in alternate years and others may switch between alternate and consecutive repeat spawning. Spawning typically occurs in November. After spawning, adults (known as "kelts") may return to the sea or may remain in fresh water until the following spring.

Eggs are deposited in nests (referred to as "redds") excavated in the gravel substrate. Hatching begins in April, and the yolk-sac larvae (known as "alevins") remain in the gravel until May or June. After emergence from the gravel, the young (now called "fry") begin feeding. As they grow, their behaviour changes and they tend to be found in different places in the river. By autumn, they are referred to as "parr". Parr in ECB rivers typically remain in fresh water for two to four years, although as described in Section 2.4, most leave the rivers at age-2 or age-3. Prior to leaving the river, parr undergo physical changes that allow them to survive in the ocean. These juvenile salmon are now referred to as "smolt" and will migrate to the sea during late April, May and early June. Timing of the smolt run varies somewhat with environmental conditions. Some male parr become sexually mature at a small size while still in the river (these are called "precocious parr"). Within the ECB populations, salmon mature after either one or two winters at sea (called "one sea-winter salmon" or 1SW, "two sea-winter salmon" or 2SW, respectively), although a small proportion also mature after three winters at sea (called "three sea-winter salmon" or 3SW). The proportion of salmon maturing after a given number of winters at sea is highly variable among populations. In general, rivers flowing off the Cape Breton Highlands contain populations that predominantly mature as 2SW salmon and have a low frequency of repeat spawning, whereas populations in the southeast portion of ECB mature predominantly as 1SW salmon and contain a higher proportion of repeat spawning salmon (Gibson and Bowlby 2009). The terms "small salmon" and "large salmon" are frequently used. Small salmon are <63 cm fork length and are virtually all 1SW first-time spawning salmon. Large salmon are ≥63 cm fork length, and include 2SW salmon, 3SW salmon, as well as repeat spawning salmon ("multi-sea-winter" or MSW).

2.2 BACKGROUND

Gibson and Bowlby (2009) describe the model used to estimate the abundance of salmon in Middle and Baddeck rivers. The model is index-based, and annual abundance estimates are obtained by estimating the annual spawning escapement, the proportion of the spawning escapement that is in the small category, and a set of coefficients used to scale the available indices (the dive counts, recreational catch and electrofishing data) to the abundances using

maximum likelihood. An advantage of this model is that it provides estimates of the number of large and small salmon in the population, as well as the proportion of the conservation requirement attained, values that are used as the basis for fisheries management. A disadvantage of the model is that it does not provide information about the productivity of the populations, a decision that was made because there is very little information available about the annual age composition of these populations. This is information that is needed to assign proportions of the spawning run each year back to the cohorts that contributing to the run. Here, the model presented by Gibson and Bowlby (2009) is adapted to estimate the productivity of the populations and is used to evaluate whether productivity has changed during the last three decades. Although the model is considered by the authors to be sufficient for this purpose, the annual abundance estimates produced by the Gibson and Bowlby (2009) model are preferred for assessment purposes because the data used in the productivity model are not sufficient to estimate the annual proportions at age in each cohort, a factor that contributes to annual variability in run size.

2.3 THE PRODUCTIVITY MODEL

The major differences in the assessment model (Gibson and Bowlby 2009) and the productivity model described here is that the spawning escapement and the proportion of the escapement that is in the small category each year are directly estimated in the assessment model, whereas in the productivity model, a set of productivity parameters (i.e., the Beverton-Holt spawner-recruit parameters, the average proportions of each cohort undergoing smoltification by freshwater age, and the average proportions of each cohort maturing by sea-age) are estimated and used to project the population forward through time from an estimated starting population size and age structure. The annual returns and escapement are then derived from these projections, under the assumption that the proportions-at-age with a cohort are constant through time. For the productivity model, the objective function of the assessment model was modified by adding a term for fitting the proportions-at-age. Additionally, the productivity model was not fit to the electrofishing data because there are only a few years with data and the inclusion of these data had very little effect in the assessment model.

The approach being used builds on theory developed for other populations. The assessment model was originally adapted from the approach used by Gibson and Amiro (2003) for Stewiacke River salmon, and Gibson et al. (2003) for Big Salmon River salmon, to estimate abundance from all available indices. This is also similar to the approach described by Rago (2001). The method used follows the general theory developed by Fournier and Archibald (1982) and Deriso et al. (1985) for statistical catch-at-age models for stock assessment that allows auxiliary data to be incorporated. There is a fisheries component to the model in the form of the basic catch equation for a Type I fishery (Ricker 1975). Auxiliary data are counts of salmon by divers at the end of the recreational fishery, as well as some information about the age composition of the population. The model is "anchored" using mark-recapture experiments carried out in some years during the snorkelling counts.

The core of the production model is a dynamical equation that gives the number of salmon returning to the river to spawn for the first time in year t, that are of freshwater age fa, and sea age sa, denoted as the three dimensional array, $N_{t,fa,sa}$, as a function of the egg depositions in earlier years, $Eggs_{t-fa-sa-1}$, a set of productivity parameters governing the survival from the egg to the adult life stages, and a set of parameters that distributes the overall adult production of the cohort to the appropriate return year using the proportions at age:

$$N_{t,fa,sa} = \frac{\alpha Eggs_{t-fa-sa-1}}{1+\frac{\alpha Eggs_{t-fa-sa-1}}{R_{asy}}} \exp(\varepsilon_{t-fa-sa-1} - \frac{\sigma^2}{2}) \prod_{i=\min(fa)-1}^{fa-1}(1-h_i)h_{fa} \prod_{j=\min(sa)-1}^{sa-1}(1-k_j)k_{sa}.$$

The first part of the equation is a Beverton-Holt spawner-recruit (SR) function that gives the total number of first-time spawning adults produced within a cohort as a function of the egg deposition in a given year and two parameters: α is the maximum survival from egg to adult in the absence of density dependence (the slope of the SR function at the origin), and R_{asy} is the asymptotic recruitment level, which is the limit that adult production approaches as the egg deposition approaches infinity.

The second part of the equation incorporates annual variability in the number of adults produced within a cohort. The term ε_t is the natural logarithm of the annual recruitment deviate, and σ^2 is the variance of these log deviates. The term $\exp(\varepsilon_{t-fa-sa-1} - \frac{\sigma^2}{2})$ returns a multiplicative factor that adjusts the annual average rate returned by the SR function for annual variability that would occur as the result of variability in survival in fresh water and at sea. The term $-\frac{\sigma^2}{2}$ corrects for transformation bias and is necessary because the recruitment deviates are estimated on the log scale.

The next two terms in the model distribute the total number of returning salmon to the appropriate return year based on the proportions that undergo smoltification at different freshwater ages, h_{fa}, and the proportions that mature at different sea ages, k_{sa}. The model includes freshwater ages 2 to 4 and sea ages 1 to 3. The proportions that undergo smoltification at each age are constrained to sum to one by defining the terms such that the age-2 smolts are first removed from the population, and the proportion undergoing smoltification at age-3 is applied to the remaining fish. Any remaining fish are assumed to undergo smoltification at age-4. As such, the actual proportion of the cohort that are age-3 smolts is $(1-h_2)h_3$ and the proportion that are age-4 is $(1-h_2)(1-h_3)$. The actual proportions of the cohort that are sea-age-1, -2, or -3 can be calculated similarly.

Although the model estimates the numbers-at-age, the adult abundance indices collected for these populations are typically characterized as the number of large and small salmon returning to the river each year, denoted here as the matrix $N_{t,s}$, where s is the size category (large or small). All first time spawning 1SW salmon are assumed to be small, and all 2SW, 3SW and repeat spawning salmon are assumed to be large, such that:

$$N_{t,small} = \sum_{fw} N_{t,fw,1},$$

and

$$N_{t,large} = \left(\sum_{fw,sw} N_{t,fw,sw} - \sum_{fw} N_{t,fw,1}\right) + 0.5\upsilon\left(\sum_{fw,sw} N_{t-1,fw,sw} + \sum_{fw,sw} N_{t-2,fw,sw}\right).$$

The first half of the equation for $N_{t,large}$ gives the number of first time spawning salmon, and the second half gives the number of repeat spawning salmon based on the proportion of salmon that repeat spawn, υ, under the assumptions that 50% of repeat spawners are alternate-year repeats and 50% are consecutive-year repeats, and that salmon in these populations spawn a maximum of two times. Although salmon that have spawned more than twice can be prevalent in some populations, of 138 salmon from the Middle River and 106 salmon from the Baddeck River that were aged from 1997 to 2004, only one salmon was identified that had spawned more than two times. The values for υ are constants in the model calculated as the proportion of salmon in aged samples that are repeats (0.034 and 0.048 for the Baddeck and Middle populations, respectively).

The predicted catch in each year and size category, $C_{t,s}$, is related to $N_{t,s}$ through the instantaneous rate of fishing mortality for each size class and year, denoted $F_{t,s}$:

$$C_{t,s} = N_{t,s}(1 - e^{-F_{t,s}}).$$

The instantaneous rate of fishing mortality for each size class and year, $F_{t,s}$, was assumed to be proportional to the fishing effort in year t, E_t, and to be related through the size-specific catchability coefficients, q_s:

$$F_{t,s} = q_s E_t.$$

The recreational catch data includes estimates of the number of salmon retained, or harvested, in each size class by the recreational fishery each year, $H_{t,s}$. A correction factor for hook and release mortality (assumed 4%) is included in the model at this point, as are recent broodstock removals. Removals from the population resulting from these two source are included in $H_{t,s}$. The spawning escapement in each year and size class, $Esc_{t,s}$, is then:

$$Esc_{t,s} = N_{t,s} - H_{t,s},$$

and the life cycle as modeled is closed by calculating the egg deposition in year t, $Eggs_t$, as:

$$Eggs_t = \sum_s Esc_{t,s} f_s.$$

Here, f_s are the sex-ratio adjusted, size-specific fecundities for each population. Values of 3,547 eggs per large salmon and 137 eggs per small salmon are used for the Middle River population, and values of 5,172 eggs per large salmon and 471 eggs per small salmon are used for the Baddeck River population (Marshall et al. 1999). These are the same values that are used in the assessment models and are used to calculate the conservation requirement.

In order to provide an index of the number of spawners each year, divers swim down these rivers each fall in late October and count the number of large and small salmon observed (Levy and Gibson 2014). The dive counts in year t, $swim_t$, are used as an index of escapement and are related to $Esc_{t,s}$ through an "observability" coefficient for the dive counts, q_{swim}:

$$Swim_t = q_{\text{swim}} \sum_s Esc_{t,s} .$$

Parameter Estimation via Maximum Likelihood

Parameter estimates were obtained by minimizing an objective function (*O.B.V.*) that is the sum of the negative log likelihoods (Quinn and Deriso 1999) for the catch (ℓ_{catch}), the dive counts (ℓ_{dive}), the age composition data (ℓ_{age}) and the mark-recapture experiments (ℓ_{m-r}) conducted during the dive surveys. The relative contribution of each likelihood to the objective function was controlled using a set of weighting values, w_i. These values may be selected to keep any one part of the objective function from dominating the fit or, alternatively, to reflect perceptions of data accuracy (Merritt and Quinn 2000). Lognormal error structures were used for catch and dive count likelihoods, a hypergeometric error structure was used for the mark-recapture likelihoods, and a multinomial error structure was used for the proportions-at-age. Superscripting observed values with "obs", the log likelihoods are:

1. Recreational Catches:

$$\ell_{catch} = -n \ln(\sigma_{catch,s})\sqrt{2\pi} - \sum_{t,s} \ln(C_{t,s}^{obs}) - \frac{1}{2\sigma_{catch,s}^2} \sum_{t,s} (\ln C_{t,s}^{obs} - \ln C_{t,s})^2 .$$

2. Dive Counts:

$$\ell_{dive} = -n \ln \sigma \sqrt{2\pi} - \sum_{t,s} \ln(swim_t^{obs}) - \frac{1}{2\sigma^2} \sum_{t,s} (\ln swim_t^{obs} - \ln swim_t)^2 .$$

For the lognormal log-likelihoods, n is the sample size for the corresponding data set and σ_x is the corresponding shape parameter (for a lognormal distribution, σ is the standard deviation of a normal distribution prior to exponentiation). σ was set equal to 0.3 for both of these likelihoods during these analyses.

3. Mark Recapture:

$$\ell_{mark-recap} = \ln\binom{m}{r} + \ln\binom{N-m}{c-r} - \ln\binom{N}{c},$$

where N is the population size estimate, m is the number of marked fish in the population, c is the number of fish examined for marks, and r is the number of fish that were examined for marks that were, in fact, marked.

4. Adult Age Composition:

$$\ell_{age} = \sum_t \log\left(\frac{n_t!}{(x_{t,1}!)(x_{t,2}!).....(x_{t,r}!)} p_{t,1}.....p_{t,r} \right),$$

where n_t is the number of age samples collected in year t, $x_{t,i}$ is the observed number of fish in age category i (e.g., *fw* = 2, *sw* = 2), $p_{t,i}$ is the estimated proportion in size category i, and r is the number of age categories (r = 9).

The objective function is:

$$O.B.V. = -(w_1 \ell_{dive} + w_2 \ell_{catch} + w_3 \ell_{age} + w_4 \ell_{m-r})$$

All weighting factors were set equal to one except for w_4, which was set equal to 5 to keep the model from producing estimates of abundance that were implausibly high during some model runs.

The model was set up to estimate the egg depositions, $Eggs_t$ for the years 1975 to 1982 (eight parameters), values that were used to initialize the starting abundance and age structure in 1983. Other estimated values are: the log recruitment deviates for the years 1983 to 2007 (25 parameters), the catchability coefficients for the recreational fisheries (two parameters estimated on the log scale) and dive surveys (one parameter); the log of the slope at the origin and the asymptotic level for the SR function (two parameters); and the proportions of each cohort that undergo smoltification at freshwater ages 2 and 3, and that matures at sea ages 1 and 2 (four parameters). The model was programmed using AD Model Builder (Fournier 1996). AD Model Builder (ADMB) uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities, and is designed specifically for fitting these types of models.

Whenever minimization is used to estimate parameters in a nonlinear model, there is a possibility of convergence to a local minimum, rather than the global minimum. Multiple iterations of the model using different starting values were run. The estimates are robust with respect to the starting values. The sensitivity of the results to the weighting of model components and small changes in model formulation were also examined, and for the most part, the results are robust with respect to these modifications.

Bayesian Analyses

Bayesian methods provide a powerful tool for assessing uncertainty in fisheries models (McAllister et al. 1994). Punt and Hilborn (1997) and McAllister and Kirkwood (1998) have reviewed their fisheries applications. The posterior probability distributions resulting from Bayesian analyses show the uncertainty in model or policy parameters including both estimation uncertainty, as well as prior information about their values (Walters and Ludwig 1993). ADMB uses a Markov Chain Monte Carlo (MCMC) algorithm (Carlin and Louis 1996) to approximate the posterior distribution for parameters of interest. MCMC is a stochastic simulation method used to evaluate complex integrals in order to derive posterior distributions. ADMB uses the Metropolis Hastings algorithm (Chib and Greenberg 1995) to generate the Markov chain, using a multivariate normal distribution based on the variance-covariance matrix for the model parameters as the proposal function. If the chain is long enough, the posteriors will be reasonably well approximated.

Uniform bounded priors were assumed for all model parameters. Bounds were generally wide enough so as not to influence the model fit, exceptions being the earliest egg depositions (see results). Posterior distributions were derived using 8,000,000 iterations of the MCMC algorithm after a burn in of 800,000 iterations, and by sampling every 8,000th iteration. This level of thinning was sufficient to ensure that autocorrelation in the chain was not overly problematic. Convergence of the Markov chain was inferred informally by comparing the similarity of the 10th and 90th percentiles of the posterior densities based on the first 4,000,000 iterations with those based on the second 4,000,000 iterations, and by comparison of the posterior densities from several chains (Gamerman 2000). Because of high covariance between some model parameters, the --mcrb option (set to 1) was used to reduce the covariance used in the proposal function, and the -mcgrope option (set to 0.7) was used to widen the tails of the proposal function (Fournier 1996). Using these two options allowed ADMB to more fully explore the parameter space but results in a less efficient search algorithm.

Equilibrium Calculations

Gibson and Bowlby (2013) summarize the role of equilibrium analyses as follows:

> "Human activities may affect some parts of a fish population's life history, such as its average fecundity, survival from one age class or life stage to the next, age-at-maturity or the number of times an individual reproduces. These parameters in turn affect the population's productivity, and one way to assess the effects of a human activity is to evaluate the expected change in productivity that results from changes in life history parameters.
>
> Equilibrium modeling is one approach that can be used to assess impacts of human activities in this way. This kind of analysis begins by splitting the life cycle of salmon into two parts, and for a given set of life history parameters, determining the population size at which the rates in each part of the life cycle are balanced such that the population does not increase or decrease in size. This is the population equilibrium for that specific set of parameter values. By varying the life history parameters in a manner that represents the expected response to a human activity and examining the resulting change in equilibrium population size, the effects of the activity on the population can be evaluated. Equilibrium models are widely used for analyzing population dynamics (Moussalli and Hilborn 1986), for estimating biological reference points for fisheries management (Myers et al. 1994), for providing a basis for the estimation of the long-term consequences of mortality caused by pollution, dams or other human activities (Barnthouse et al. 1988) and for linking fish habitat and fish population dynamics (Hayes et al. 1996)."

Because smolt abundance estimates are available for two Southern Upland populations, Gibson and Bowlby (2013) were able to divide the life cycle at the smolt stage, and analyse the dynamics from the egg to the smolt life stages (freshwater production) and the lifetime production of eggs by smolts (largely determined by marine survival) separately. In the absence of smolt abundance estimates for the Middle and Baddeck populations, this natural break cannot be made, but the life cycle can be broken into two parts at the first-time-spawning adult stage. This approach has the major disadvantage that the effects of activities occurring in fresh water cannot be separated from those resulting from activities in the marine environment, but it does allow analysis of their dynamics and viability.

In the model above, a recruit is defined as a salmon that is spawning for the first time. Assuming one repeat spawning event, the lifetime egg production per recruit is, therefore, calculated as:

$$EPR = k_1 f_s + (1 - k_1) f_l + \upsilon f_l .$$

The equilibrium egg deposition and recruitment are denoted with asterisks to differentiate them from parameters in the estimation model. The equilibrium egg deposition ($Eggs^*$) is:

$$Eggs^* = \frac{(\alpha EPR - 1)R_{asy}}{\alpha},$$

and the equilibrium number of recruits (R^*) is found by substituting $Eggs^*$ into the spawner-recruit model:

$$R^* = \frac{\alpha Eggs^*}{1 + \frac{\alpha Eggs^*}{R_{asy}}} \exp(-\frac{\sigma^2}{2}).$$

2.4 DATA INPUTS

Most the data inputs for this model are described in Section 3 of Levy and Gibson (2014). The recreational catch data are provided in tables 3.1.2 and 3.2.2 of Levy and Gibson (2014) for the Middle and Baddeck populations, respectively; and the dive counts and mark-recapture information is provided in their tables 3.1.4 and 3.2.4. The adult age composition is input differently than the way it is presented in Table 3.1.1 and Table 3.2.1 of Levy and Gibson (2014), where the freshwater age composition and sea age composition are presented separately. For the production model, both the freshwater and the sea ages must be used together in order to assign an adult back to a cohort. The numbers in each category associated with a freshwater and sea age combination for first-time spawning salmon, as it is input into the model, are provided in tables 2.1 and 2.2 for the Middle and Baddeck populations, respectively. In the model, these data are used to distribute annual recruitment among years based on the proportions in each freshwater and sea age category. There are nine of these, and the sample sizes in every year are very small for determining these proportions.

2.5 RESULTS

The productivity model fits to the data are provided in figures 2.1 and 2.2, and model parameter estimates are in Table 2.3. These results, together with model diagnostics, indicate the data for the Middle River population are somewhat informative about its productivity; however, the data for the Baddeck River population are less informative. The results suggest that the Middle River population is slightly more productive than the Baddeck River population. The results indicate little or no long term trend in the productivity of the Middle River population, whereas the productivity of the Baddeck River population may have declined slightly. These points are expanded upon below.

The fits to both the recreational catch data (Figure 2.1) and the dive surveys (Figure 2.2) indicate that the productivity model is able to capture the general pattern in these data. However, the fits are not as tight as with the assessment model (compare with the fits shown in Gibson and Bowlby 2009). This results from the model having to distribute the recruitment produced in a single year class into nine age classes that may return to the river in four different years without allowing for annual variation in the proportions at age. In contrast, the assessment model simply provides estimates of the number of large and small salmon without having to account for this underlying age structure and, therefore, provides better fits to the data.

Model fits are not entirely satisfactory for either population, but they are better for the Middle than for the Baddeck, as shown by the standard errors on the productivity parameter estimates provided in Table 2.3. For example, the standard errors for the log alpha parameter (a key determinant of overall productivity) are less than $1/10^{th}$ the parameter estimate for the Middle River population, but they are about four times the estimate for the Baddeck River population. While these asymptotic standard errors in these types of models are not a good indicator of parameter uncertainty, these differences are indicative of differences in the model fit. This problem is exacerbated for the derived values, such as the equilibrium egg deposition, that are combinations of the estimated parameters (Table 2.4).

This issue was further explored using the MCMC output from the Bayesian part of the analysis. Even though the proposal functions were set up to allow the algorithm to fully explore the parameter space, the resulting Markov chains were not ideal for either population.

Autocorrelation was markedly reduced in the chains for the Middle River population but remained problematic for the Baddeck River population. Notwithstanding this issue, the posterior distributions for model parameters (discussed below) tended to be reproducible for both populations, giving some support to the idea that the results are credible, although convergence of the chain cannot be assured, particularly for the Baddeck River population.

Because the log(alpha) parameter is the primary determinant of the overall productivity of the populations, the information content of this data and model combination with respect to productivity can be evaluated by visual examination of plots of the objective function values against the log(alpha) parameter for each step of the Markov chain (Figure 2.3) This examination indicates that the data is fairly informative about the productivity of the Middle River salmon population, as is shown by the dish-shaped profile formed by the points at the bottom of the plot, indicative that a minima is present. In contract, for the Baddeck River population, there is less information in the data with respect to productivity as indicated by the relatively flat bottom profile formed by the points. However, the data do appear to be informative within broader bounds. Stated another way, for the Baddeck population, the model is able to fit the data similarly well using a wider variety of parameter estimates, which leads to uncertainty about any single parameter estimate.

Of interest is a comparison of the abundance trends produced using the productivity model (Figure 2.4) and the assessment model (figures 3.1.1 and 3.2.1 in Levy and Gibson (2014)). For both populations, the productivity model results show less annual variability than the results of the assessment model because of the additional model structure already discussed. Additionally, the estimates of the catchability coefficients for the recreational fishery and the observation coefficient for the dive surveys are slightly lower when estimated with the productivity model, resulting in slightly higher estimates of abundance, but these differences are not large and, in general, the overall abundance trends from the two analyses are fairly similar.

One advantage of the productivity model formulation is that the trends or temporal patterns in the recruitment deviates are informative about changes in the overall productivity of the populations. For the Middle River population, there is no trend in the recruitment deviates (Figure 2.5), indicating no long term trend in productivity from the mid-1980s until present. The pattern is different for the Baddeck River population where a slight decrease in productivity over the time period is evident (the majority of positive deviates are at the beginning of the time series). This difference between the populations is likely not an artefact of the productivity model or parameter uncertainty because the assessment models also show a 20-year abundance decline for the Baddeck River population that was not evident for the Middle River population (Table 3.6.2, and figures 3.1.2 and 3.2.2 in Levy and Gibson (2014)).

The estimated annual recruitments (Figure 2.5) show variability that can exceed a factor of five annually. While the general recruitment patterns are similar, there is a marked difference in the predicted recruitment resulting from the 2006 and 2007 year classes between the rivers. Because 2SW adults and repeat spawners from these year classes have not yet returned, there is some uncertainty about whether this difference is real. However, if it is real, it would be expected that abundance will continue to be high in the Middle River in the next couple years but will decline in the Baddeck River.

Notwithstanding the issues with the information content in the data, the parameter estimates do suggest some differences in the dynamics of the populations. As shown in Figure 2.6 and with the parameter estimates in Table 2.3, the age structure of the populations may differ. Based on the adult ages, there is both a higher portion of age-2 smolts and a lower portion of age-3 smolts in Middle River than in the Baddeck River. This implies that a single year class has its smolts more evenly distributed over the three smolt age classes (2 to 4) in the Middle River, whereas there is a greater portion of age-3 smolts within a cohort in the Baddeck River. Maturity

after one winter at sea is similar in the two populations, but there is the potential for a slightly greater proportion of 3SW salmon in the Middle River (inferred from the parameter posterior distribution of the proportion maturing as 2SW salmon in Figure 2.6). Together with the differences in the ages-at-smoltification, this would help to distribute the reproductive effort of a single year class over more years, a strategy thought to buffer against the effects of annual variability in survival. As discussed earlier, salmon in the Baddeck River tend to be larger and have a higher fecundity. This difference results in a higher lifetime egg production per recruit in the Baddeck River than in the Middle River (Table 2.4) even though the frequency of repeat spawning (based on the limited available age data) is higher in the Middle River population.

Also, notwithstanding the issues with the information content of the data, the asymptotic recruitment levels are roughly similar between these populations (Table 2.3, Figure 2.7), with the maximum likelihood estimates (MLEs) differing by about 10%. Interestingly, this result is not inconsistent with the differences in the amount of rearing habitat (about 3%), although the difference in the asymptotic recruitment levels could potentially arise due to the earlier age at smoltification on the Middle River rather than the amount of habitat available for each population. The average maximum survival from the egg to the recruit stage (indicated by log(alpha)) is also estimated to be lower in the Baddeck River (Table 2.3, Figure 2.7), which could in part be due to the differences in the age of smoltification, or because productivity appears to be slightly declining for the population. Overall, the M.L.E.'s of the maximum lifetime reproductive rate are 3.22 and 1.61 spawners per spawner for the Middle and Baddeck populations (Table 2.4), indicating that the Middle River population may have greater resiliency to environmental events than the Baddeck River population. Based on the posterior distributions for this model parameter (Figure 2.7), this difference between populations may not be as large as indicated by the MLEs. If so, it is more likely that the maximum lifetime reproductive rate for the Baddeck population is nearer that of the Middle population than the rate for the Middle population is as low as that for the Baddeck.

Given the dynamics described in this section, both populations have equilibriums that are slightly greater than 50% of their conservation requirement (Table 2.4, Figure 2.8), although these are achieved differently in the two populations. The Middle River population produces a greater number of recruits but with a lower lifetime egg production per recruit than does the Baddeck River population (Table 2.4). For both populations, the estimated egg depositions and recruitments are scattered around the equilibrium (Figure 2.8), consistent with the populations having fluctuated in size at about 50% of their conservation requirement during the time period that data is available.

3.0 POPULATION VIABILITY ANALYSES

3.1 INTRODUCTION AND BACKGROUND

The long term population projections required to address objectives 5, 25, 26 and 27 were carried out using a population viability analysis (PVA). PVAs are used extensively in conservation biology to predict both the risk of extinction for populations and species and to evaluate management strategies to recover at-risk populations. In a PVA, a population dynamics model is used to determine how the probability of persistence is affected by current conditions and future perturbations (Beissinger and McCullough 2002). Models are often used to identify threats to the persistence of a population and to evaluate how future management actions or environmental changes may influence the probabilities of extinction or of achieving recovery goals (Reed et al. 2002). Using simulations of population trajectories, PVA allows one to explore the logical implications of current knowledge and assumptions (Bowlby and Gibson 2011).

Although some authors have cautioned against the use of PVAs because the predictions, typically time to extinction, are almost always quite uncertain (e.g., Taylor 1995; McCarthy et al. 1996; Ludwig 1999), many authors believe that PVAs can be used to assess relative risk (e.g., Akçakaya and Raphael 1998; Beissinger and Westphal 1998; McCarthy et al. 2001). Reed et al. (2002), argue that these relative evaluations are the most appropriate use of PVAs and can be used as a basis for choosing the most effective management strategy from a given set of possibilities (Lindenmayer and Possingham 1996). With respect to selecting recovery strategies, McCarthy et al. (2003) used a simulation study and found that they were able to identify the better of two management strategies 67–74% of the time using 10 years of data, and 92–93% of the time with 100 years of data.

The output of a PVA is often presented as the probabilities of extinction and of recovery as a function of time. Correctly interpreted, this information can be very useful, but can be quite misleading if misinterpreted. As discussed below, the inputs to the PVA consist of a set of parameters that characterize the productivity and size of a population, together with another set of parameters that characterize how the population's productivity varies over time. The output of the PVA is conditional on these inputs, and it shows whether a hypothetical population governed by these inputs and the dynamical equations would be expected increase or decrease over time, as well as how long it would take this population to recover or to become extinct. Additionally, varying the inputs can be used to assess how much of a change in productivity is required in order for a population to recover. As discussed above, this can be very useful for selecting among management strategies. However, the PVA does not show how the real population will respond to actions or inaction in the future because, even though the PVA may be set up using population-specific data, future environmental conditions on time scales of generations are not known. For this reason, the PVA output should not be interpreted as a prediction of the true state of the future population, but rather should be interpreted conditionally on the model dynamics, intended to be representative of current conditions, remaining unchanged.

Some relatively simple PVA models are possible. For example, the Dennis-type PVA (Dennis et al. 1991) can be used to evaluate extinction risk if the assumption is made that future trends will be similar to past trends, although this type of model is of limited utility for evaluating recovery actions because the underlying biology is not considered. Models that track abundance at multiple life stages are, therefore, preferred when evaluating population persistence (O'Grady et al. 2004), provided adequate data are available and uncertainties are accounted for (Holt and Peterman 2008; Legault 2005; McCarthy et al. 2001). In comparison with salmon populations in other DUs, there are few data available for salmon populations in eastern Cape Breton, although the information provided in Section 2 is sufficient to develop a PVA for both the Middle and Baddeck rivers. However, in contrast with the inner Bay of Fundy, outer Bay of Fundy and Southern Upland Atlantic Salmon DUs, separation of the life cycle into freshwater and marine components in order to evaluate the effects of recovery actions in those two environments separately was not possible. This is due to the lack of information about the smolt runs within the ECB DU.

The PVA model used here is an adaptation of the population dynamics model used to estimate life history parameter values in Section 2. The model is age-structured and tracks the abundance of all adult age classes and egg depositions for the duration of the forward projection. Autocorrelated random variability is added around the productivity model governing the survival from the egg to the adult life stages, as well as to the proportions of adults in each freshwater- and sea-age class. As the strength of this autocorrelation increases, good years are increasingly likely to be followed by good years (and bad followed by bad). Details are provided in Section 3.2.

Additionally, because Atlantic Salmon occupy habitats that are periodically subject to extreme conditions (e.g., floods and droughts), the effects of extreme events (which can lead to very high mortality) were included in the model. In this analysis, extreme events are assumed to affect survival before density-dependent processes occur in the life cycle. This approach allows density-dependent compensation to occur, which would partially offset some of the mortality, and the effect of the extreme events would be greater if it was incorporated after density dependence in the life cycle. Analyses of the timing of density dependence in salmon in the Maritime Provinces provide evidence that most density dependence occurs between the fry and the age-1 parr life stages (Gibson 2006). For this reason, the way the extreme environmental events are modeled could be considered to represent events that effect survival from the egg (at the time of spawning) to the fry life stages.

The PVA analyses are specific to the Middle River and Baddeck River salmon populations, and they should not be considered representative of populations with different characteristics, such as those in the southeast portion of eastern Cape Breton.

3.2. MODEL DESCRIPTION

The PVAs were carried out using a forward projecting population model developed specifically for the life history and data available for ECB Atlantic Salmon (specifically the Middle and Baddeck populations). The dynamical model (i.e., describing the life history) is identical to the one described in Section 2. These dynamical equations are used to project the population forward from the starting age-specific adult abundances and egg depositions obtained in Section 2 for the time period 2003-2011. For the projections under current conditions, the life history parameter values from Section 2 are used.

Random variability was incorporated into the productivity relationship, and into the smoltification and maturity schedules for greater biological realism (Shelton et al. 2007). A lognormal distribution was used for the deviates around the productivity relationship, and a logistic distribution for the probabilities of smoltification at freshwater ages 2 and 3, as well as the proportion maturing after one or two winters at sea. Lognormal distributions are often used to model the deviates around survival functions as survival is multiplicative in nature (Hilborn and Walters 1992). Given that sex ratio and maturity are proportions, the logistic transformation better describes the binomial characteristics of their error distributions.

Deviates are expected to be temporally autocorrelated (Hilborn 2001), given that the effect of environmental variability on population vital rates tends not to be completely random (Lande et al. 2003). As the strength of this autocorrelation increases, good years are increasingly likely to be followed by good years (and bad followed by bad).

In instances where comparisons were made between scenarios, the same set of random numbers was used to generate variability in parameter values to ensure that the differences between the scenarios do not occur by chance (i.e., because a different set of numbers was used).

Lognormal Variability in Productivity

Let ε_t be the log of the recruitment deviate for the cohort t, σ_w equal the standard deviation of these deviates and d be a constant describing the degree of autocorrelation. The deviate used in the forward projection for cohort t is given by:

$$\varepsilon_t = w_t - \frac{\sigma_w^2}{2},$$

where

$$w_t = (w^*_{t-1}\, d + w^*_t)\sigma_w,$$

and

$$w^*_t \sim N(0,1).$$

The total number of adult salmon in cohort t (N_t) is then calculated as:

$$N_t = \frac{\alpha E_t}{1 + \frac{\alpha E_t}{R_{asy}}} e^{\varepsilon_t}.$$

Logistic Variability in Proportions at Age in the Adult Population

The simulated total number of adult salmon are then distributed to the appropriate spawning year using the proportions at freshwater ages 2, 3 and 4 and sea ages 1, 2 and 3 as described below.

Let p be the mean parameter value in the form of a proportion. The logit mean of the parameter (S) becomes:

$$S = \ln(p/(1-p)).$$

Autocorrelated random deviates for t years are calculated as:

$$w_t = (w^*_{t-1}\, d + w^*_t)\sigma_w,$$

where

$$w^*_t \sim N(0,1),$$

and d and σ_w are as described above.

The annual probability becomes:

$$p_t = \exp(S + w_t)/(1 + \exp(S + w_t)).$$

Here p_t can be any of the simulated probabilities that an adult salmon had become a smolt at freshwater ages 2 or 3 or had matured at sea ages 1 or 2. As was the case in the parameter estimation model for the age of smoltification, the proportions are constrained to sum to one by first removing the age-2 smolts from the population, and the proportion smoltifying at age 3 is applied to the remaining fish. All fish are assumed to smoltify by age 4.

Random Variability and Autocorrelation

Ideally, the amount of random variability and strength of autocorrelation would be derived from the statistical life-history model output. Time series models were used to evaluate

autocorrelation in the annual estimates of the log recruitment deviates ε_t. Autocorrelation was estimated at time lags of zero to 15 years for both the Middle River and Baddeck River populations, but the resulting estimates of the autocorrelation coefficients were not significant (Figure 3.1). As an alternative, the autocorrelation coefficient for the productivity function was set to 0.4, and its standard deviation, σ, to 0.475 for the PVAs for both populations based on a similar analysis of the return rate time series for the LaHave River and St. Mary's River salmon populations (Gibson and Bowlby 2013). This alternative would result in higher estimates of extinction risk than if no autocorrelation was assumed.

All other parameters had assumed values for autocorrelation and the amount of random variability applied. The same autocorrelation coefficient value (0.4) was assumed for the proportions-at-age as was used for the productivity function, but the standard deviation was assumed to be lower ($\sigma = 0.3$). Within limits, the general extinction patterns are not overly sensitive to changes to the variances (i.e., higher or lower values for σ), although the time to extinction does vary as more or less variability is assumed. Extinction risk is sensitive to the amount of autocorrelation that is assumed; risk increases as the autocorrelation is increased.

Catastrophic Events

Atlantic Salmon occupy naturally variable habitats that are periodically subject to extreme conditions. Floods and droughts in fresh water are examples of these, both of which can lead to very high mortality in one or many of the juvenile life stages. The effects of extreme events are included in the model using two parameters. The first parameter is the frequency parameter, ψ, which is the expected frequency of these events in a given number of years. A random number, υ_t, is drawn from a uniform distribution [0,1] for each year in each simulated population trajectory, and the value $1/\psi$ is compared to υ_t. If $1/\psi < \upsilon$, that year is considered an extreme event year. The second parameter, ϑ, is used to model the effect of the event. In this analysis, the effect of the event was included between the egg and the fry life stages, thereby allowing density-dependent compensation to occur, which would partially offset some of the mortality (because the survival of age-0 to age-1 increases as population size decreases). The effect of the extreme events would be greater if it was incorporated after density dependence. The simulated egg deposition used in next step of the projection, E_t, is then:

$$E_t = \begin{cases} Egg_t \vartheta & \text{if } 1/\psi < \upsilon_t,\ \upsilon_t \sim \text{unif}[0,1] \\ Egg_t & \text{otherwise} \end{cases}.$$

In the absence of specific information about the frequency and effects of extreme events, values of 10 and 0.33 were assumed for ψ and ϑ, respectively. This means that, on average, 10 events reducing the abundance of fry by 2/3^{rds} from the expected value would occur every 100 years. As modeled, a greater or lesser number of extreme events could occur in any simulated population trajectory, and their distribution through time is random. The sensitivity of the results to these assumed values was evaluated by running scenarios with no extreme events, as well as scenarios with more extreme environmental events.

Populations are modeled as closed populations, meaning that they are not affected by either immigration or emigration. For each scenario analyzed with the PVA, 1,000 population trajectories were simulated and the extinction and recovery probabilities were calculated as the proportion of populations that go extinct by a specified time. To evaluate extinction probabilities, a quasi-extinction threshold of 15 adult salmon was assumed. This means that annual egg

deposition is given a value of zero if the abundance drops below 15 adults. However, if adult abundance is higher in the next year, the egg deposition is calculated as per the model. A population can, therefore, sit on the quasi-extinction threshold for a number of years and can theoretically recover unless there are several sequential years where the adult abundance is less than 15. When evaluating recovery probabilities, the conservation requirement was used as the recovery target. Similarly, populations may sit at the recovery threshold and then go into decline, at which point they are no longer considered recovered.

Abundances for each life stage were projected forward for 100 years even though there is considerable uncertainty about what the dynamics of these populations will be at that time. However, the reason for using these long term projections is not to estimate what abundance will be in a particular year, but rather to evaluate longer term viability for each scenario (i.e., does the projection go to zero or not). In other words, the longer term projections are used to determine whether the populations are viable for each combination of life history parameters, random variability and extreme events included in the scenario.

3.3 RESULTS

Population Viability under Current Conditions

Five example abundance trajectories for the Middle River and Baddeck River populations are provided in Figure 3.2, where they can be compared with the 1983-2011 abundance estimate time series. In general, these simulated trajectories are not dissimilar to the 1983-2011 time series, but they potentially show slightly greater variability. Simulated abundance reached the conservation requirement intermittently but does not remain above it for any period of time.

The summaries of the 1,000 simulated abundance trajectories for the Middle River and Baddeck River populations indicate that, if the dynamics derived in Section 2 remain unchanged, there is low probability that either population will reach its recovery target or extirpate (Figure 3.3). The probability of extinction (Table 3.1, Figure 3.4) remains less than one percent for both populations over the 100 year time series, whereas the probability of recovery (or more accurately the proportion of the populations that are above the recovery target in any year) is in the vicinity of 5% for the Middle River population and of 3% for the Baddeck River population. The median abundance is slightly below the estimated equilibrium because of the way random variability is included. The pattern shown in Figure 3.2 where populations do not remain above the recovery target is the same for the 1,000 simulated trajectories as well. Additionally, these statements are conditional on the modeled dynamics remaining unchanged over the duration of the simulation. If the dynamics change in the future, extinction and recovery probabilities will also change.

Population Viability Analysis of Recovery Scenarios and Increased Levels of Mortality

Specific recovery scenarios were not available for these analyses, so, to evaluate how the probability of extinction and probability of meeting the recovery target would be expected to vary with increased productivity (with could occur in either fresh water or at sea), six scenarios were evaluated for both the Middle River and Baddeck River salmon populations.

Increased productivity was modeled by increasing overall survival from the egg to the first time spawning adult stage by factors of 1.0 (no increase), 1.2 (20% increase), 1.5 (50% increase) and 2.0 (double or 100% increase). Similarly, decreased productivity was modeled by decreasing survival to 90%, 70% and 50% of the base model level.

Abundance trajectories, extinction probabilities and recovery probabilities for the increasing productivity scenarios are provided in figures 3.5, 3.6 and 3.7 for both populations. The results differ between the populations due to the differences in estimated productivities. In the case of the Middle River population, increasing the productivity by 50% (which could happen if the

returns rates increased by 50%, going from 2% to 3% as a hypothetical example) results in one third of the simulated populations being above the recovery target after 20 years (Table 3.2). In the case of the Baddeck River population, despite its lower productivity but due to its slightly higher estimated asymptotic recruitment level, this proportion is just over 0.4.

Similarly, the results for the decreasing scenarios are provided in figures 3.8, 3.9 and 3.10. In the case of the Middle River population, decreasing productivity by 50% only slightly increases the extinction risk over 50 years (Table 3.2), whereas a 50% decrease in productivity for the Baddeck River population increases its extinction risk to over 95% in 50 years.

4.0 DISCUSSION AND CONCLUSIONS

During the last two decades, data collection for salmon populations in eastern Cape Breton has been focused on collecting information for estimating the annual population size (returns and spawning escapement). While these collections have fulfilled this purpose for the Middle and Baddeck populations, the data are not sufficient to fully analyse their dynamics. The inner Bay of Fundy, outer Bay of Fundy and Southern Upland Atlantic Salmon DUs all have populations where adult and smolt assessments are conducted, which allows for the evaluation of changes in both freshwater productivity and marine survival (Gibson et al. 2009, Gibson and Bowlby 2013). In contrast, there are no populations in eastern Cape Breton for which these evaluations can be made, and the very limited amount of age data available for the Middle and Baddeck populations undermines the certainty with which their dynamics can be discussed.

Notwithstanding these issues, the analysis of the dynamics of the Middle and Baddeck salmon populations indicates that these populations are much healthier than the salmon populations in the St. Mary's River (West Branch) and the LaHave River (above Morgans Falls), the index populations for the Southern Upland Atlantic Salmon DU. The extent of declines and changes in productivity, as inferred by the changes in survival at sea for these Southern Upland populations is greater than for Middle and Baddeck populations (Gibson and Bowlby 2013). When considering the changes in the productivity of these populations, marked declines in the Southern Upland return rates are evident from the mid-1980s that are potentially ongoing (Gibson and Bowlby 2013). This pattern was not detected in the analyses for the Middle and Baddeck populations. However, these ECB populations have a large proportion of 2SW spawners, whereas the Southern Upland populations have a much higher proportion of 1SW. Whether the productivity changes exhibited by Southern Upland salmon are indicative of changes in the ECB 1SW populations is unknown; however, given the declines in the Grand River population (Levy and Gibson 2014), which is also predominantly a 1SW population, this possibility cannot be discounted.

Under current conditions, the analyses presented here indicate a low probability of extirpation for the Middle and Baddeck salmon populations. Given the differences in life history strategies among ECB salmon populations, it would be inappropriate to make inferences about the dynamics and viability of other ECB populations based on the analyses presented for the Middle and Baddeck populations. The dynamics of other populations (as well as the status for many populations) is simply not known. A first step in the management and recovery planning for ECB populations would be to increase data collection, including smolt assessments and collections of adult age data on the currently assessed populations, as well as more widespread surveys to ascertain the status of populations about which very little is known.

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6.0 TABLES

Table 2.1. Summary of the ages of first time spawning Atlantic Salmon in Middle River as determined from scales collected from fish captured by seining for the years 1995-1998, 2000, 2003 and 2004. Only fish for which both freshwater (age of smoltification) and sea age (at maturity) were determined are included. The count is the number of fish in each category.

Year	Freshwater age	Sea age	Count
1995	2	2	2
1995	3	1	1
1995	3	2	7
1995	4	2	1
1996	3	1	5
1996	3	2	6
1997	2	1	2
1997	2	2	11
1997	3	1	8
1997	3	2	15
1997	4	1	2
1998	2	2	1
1998	3	1	5
1998	3	2	7
1998	4	2	1
1998	4	3	2
2000	3	1	1
2000	3	2	2
2003	2	1	2
2003	2	2	11
2003	3	1	3
2003	3	2	3
2004	2	1	1
2004	2	2	9
2004	2	3	1
2004	3	1	3
2004	3	2	1

Table 2.2. Summary of the ages of first time spawning Atlantic Salmon in Baddeck River as determined from scales collected from fish captured by seining for the years 1995-1998, 2003 and 2004. Only fish for which both freshwater (age of smoltification) and sea age (at maturity) were determined are included. The count is the number of fish in each category.

Year	Freshwater age	Sea age	Count
1995	2	2	2
1995	3	1	5
1995	3	2	12
1995	3	3	1
1996	2	1	2
1996	2	2	3
1996	3	1	2
1996	3	2	6
1997	2	1	2
1997	2	2	5
1997	3	1	5
1997	3	2	18
1998	2	2	1
1998	3	1	1
1998	3	2	4
1998	4	2	1
2003	2	1	1
2003	2	2	6
2003	3	1	3
2003	3	2	3
2004	2	2	1
2004	3	2	1

Table 2.3. Maximum likelihood estimates (M.L.E's) and standard deviations (Std. Dev.) for the productivity model parameters for the Middle River and Baddeck River Atlantic Salmon populations.

		Middle River		Baddeck River	
Year	Parameter	M.L.E.	Std. Dev.	M.L.E	Std. Dev.
na	dive_q	0.45	0.03	0.40	0.03
na	fishing_q_s	-6.60	0.13	-6.09	0.15
na	fishing_q_l	-7.12	0.09	-6.15	0.12
na	p2FW	0.33	0.03	0.25	0.05
na	p3FW	0.94	0.02	0.99	0.01
na	p1SW	0.20	0.01	0.21	0.02
na	p2SW	0.97	0.02	0.99	0.01
na	Log_alpha	-6.45	0.40	-7.58	28.93
na	Rasy	835.72	171.19	929.61	65483.00
1975	start_eggs	10000.00	201.17	10000.00	4760.70
1976	start_eggs	10000.00	110.53	10000.00	495.69
1977	start_eggs	102780.00	127840.00	333450.00	6901500.00
1978	start_eggs	133010.00	151670.00	270600.00	6211500.00
1979	start_eggs	312570.00	400420.00	147270.00	4045700.00
1980	start_eggs	4791000.00	21447000.00	541260.00	7074900.00
1981	start_eggs	10000000.00	234.50	1088700.00	7644200.00
1982	start_eggs	173330.00	252910.00	1354500.00	22657000.00
1983	Log_recdev	2.00	0.07	1.79	22.28
1984	Log_recdev	-2.00	0.22	-0.15	17.71
1985	Log_recdev	1.08	0.17	1.44	17.16
1986	Log_recdev	-0.23	0.32	0.39	4.13
1987	Log_recdev	-1.05	0.59	0.07	4.13
1988	Log_recdev	0.07	0.21	-1.02	9.39
1989	Log_recdev	-0.20	0.25	-0.11	10.76
1990	Log_recdev	0.20	0.19	0.79	2.24
1991	Log_recdev	0.45	0.17	-0.01	14.59
1992	Log_recdev	-0.04	0.18	-0.26	6.50
1993	Log_recdev	0.04	0.19	0.34	1.69
1994	Log_recdev	-0.43	0.23	-0.11	6.40
1995	Log_recdev	-0.33	0.29	-0.96	8.74
1996	Log_recdev	-1.66	1.12	-0.94	15.79
1997	Log_recdev	0.41	0.21	-0.01	7.95
1998	Log_recdev	0.09	0.20	-0.20	3.27
1999	Log_recdev	0.41	0.19	-0.21	6.61
2000	Log_recdev	-0.04	0.35	0.49	6.36
2001	Log_recdev	0.43	0.33	0.42	10.88
2002	Log_recdev	-0.75	1.19	-0.33	4.89
2003	Log_recdev	0.47	0.47	0.43	3.85
2004	Log_recdev	-0.50	2.10	-0.06	0.48
2005	Log_recdev	-0.57	4.04	-2.00	1.31
2006	Log_recdev	0.44	2.80	0.97	6.33
2007	Log_recdev	1.71	1.46	-0.77	11.60

Table 2.4. Maximum likelihood estimates (M.L.E's) and standard deviations (Std. Dev.) for equilibrium values estimated with the productivity models for the Middle River and Baddeck River Atlantic Salmon populations.

	Middle River		Baddeck River	
Parameter	M.L.E.	Std. Dev.	M.L.E	Std. Dev.
Lifetime egg production per recruit (number of eggs)	3,022.80	43.31	4,355.40	74.78
Equilibrium egg deposition (number of eggs)	1,180,900.00	124,620.00	1,116,600.00	14,588,000.00
Equilibrium recruitment (number of first time spawning adults)	390.67	40.68	256.37	3,349.30
Maximum lifetime reproductive rate (spawners/spawner)	3.22	1.27	1.61	53.01

Table 3.1. Probabilities of extinction and of recovery within 1 to 10 decades for the Middle River and Baddeck River Atlantic Salmon populations. Probabilities are calculated as the proportion of 1000 Monte Carlo simulations of population trajectories that either became extinct or met the recovery target.

Number of Years	Probability of Extinction		Probability of Recovery	
	Middle	Baddeck	Middle	Baddeck
10	0.000	0.000	0.040	0.042
20	0.000	0.000	0.028	0.038
30	0.000	0.000	0.054	0.044
40	0.000	0.000	0.040	0.042
50	0.000	0.002	0.060	0.044
60	0.000	0.000	0.038	0.020
70	0.000	0.002	0.040	0.032
80	0.000	0.004	0.050	0.034
90	0.000	0.004	0.064	0.040
100	0.000	0.002	0.034	0.024

Table 3.2. Proportions of 1,000 simulated population trajectories that either go extinct or meet the recovery target within 10, 20, 30 and 50 year time horizons based on productivity scenarios for the Middle River and Baddeck River Atlantic Salmon populations. The productivity scenarios reflect changes from the present levels estimated with the productivity models and include both increasing and decreasing productivity ranging from one half to twice the productivity estimates.

Population	Productivity Scenario	% of Base Scenario	Proportion Extinct				Proportion Recovered			
			10 years	20 years	30 years	50 years	10 years	20 years	30 years	50 years
Middle River	Base	100	0.000	0.000	0.000	0.000	0.040	0.028	0.054	0.060
Middle River	Increasing	120	0.000	0.000	0.000	0.000	0.104	0.140	0.148	0.136
Middle River	Increasing	150	0.000	0.000	0.000	0.000	0.272	0.324	0.338	0.340
Middle River	Increasing	200	0.000	0.000	0.000	0.000	0.578	0.610	0.638	0.606
Middle River	Decreasing	90	0.000	0.000	0.000	0.000	0.026	0.008	0.028	0.036
Middle River	Decreasing	70	0.000	0.000	0.000	0.000	0.002	0.002	0.000	0.006
Middle River	Decreasing	50	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.000
Baddeck River	Base	100	0.000	0.000	0.000	0.002	0.042	0.038	0.044	0.044
Baddeck River	Increasing	120	0.000	0.000	0.000	0.002	0.114	0.148	0.170	0.144
Baddeck River	Increasing	150	0.000	0.000	0.000	0.002	0.294	0.414	0.434	0.426
Baddeck River	Increasing	200	0.000	0.000	0.000	0.002	0.622	0.726	0.784	0.746
Baddeck River	Decreasing	90	0.000	0.000	0.000	0.014	0.022	0.010	0.014	0.014
Baddeck River	Decreasing	70	0.000	0.016	0.040	0.274	0.004	0.000	0.000	0.000
Baddeck River	Decreasing	50	0.000	0.258	0.622	0.968	0.000	0.000	0.000	0.000

7.0 FIGURES

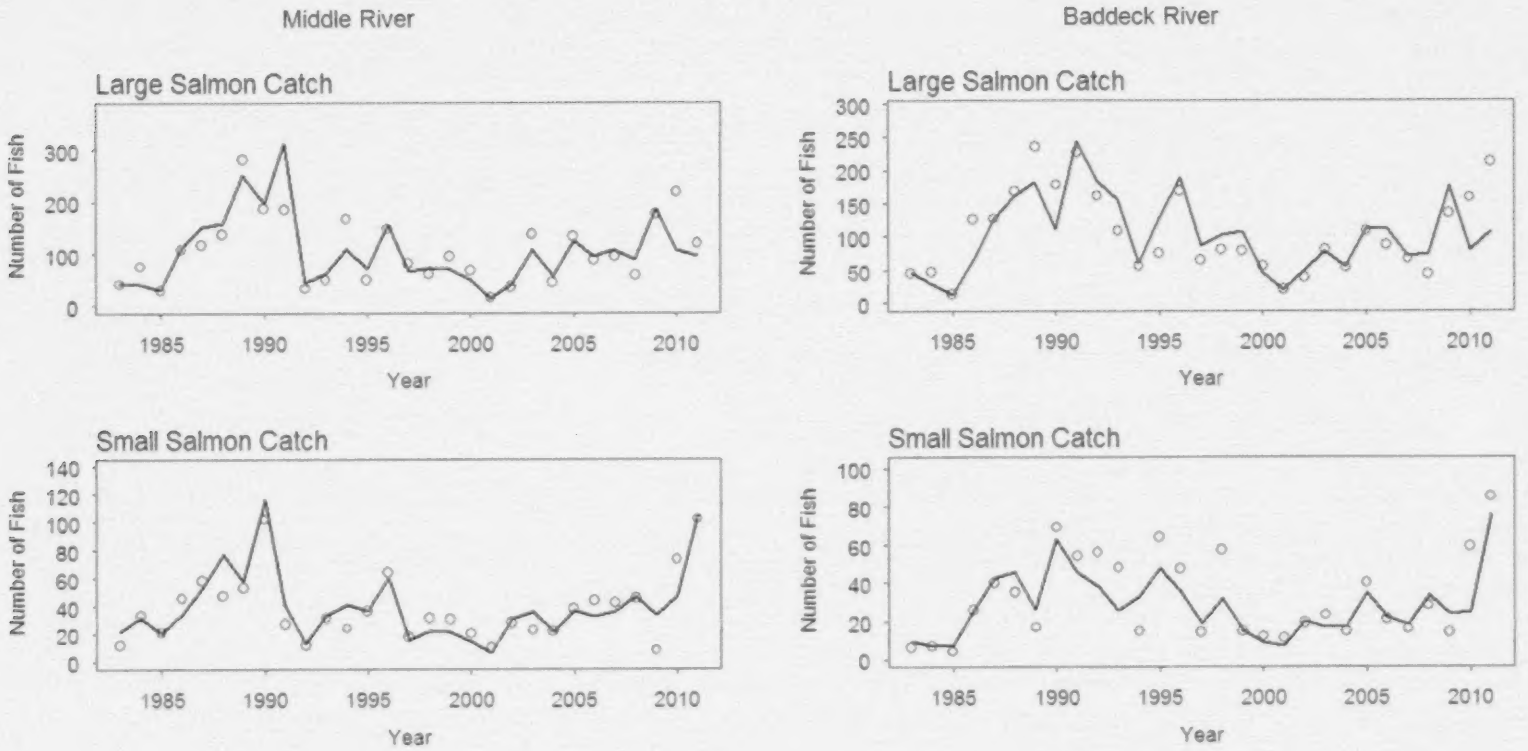

Figure 2.1. Observed (points) and estimated (lines) Atlantic Salmon catches on the Middle River (left column), and Baddeck River (right column), NS, from 1983 to 2011, showing the productivity model fits to these data.

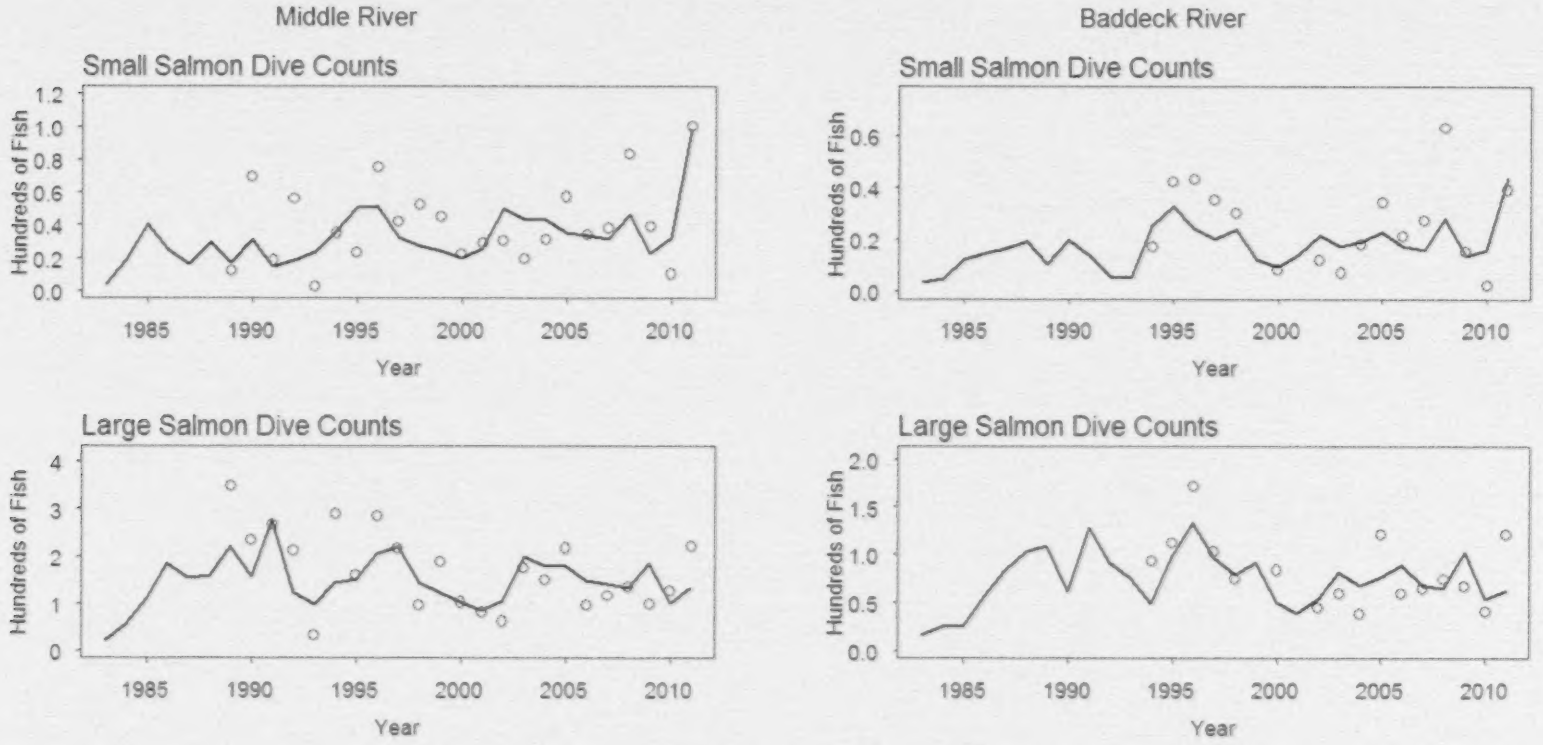

Figure 2.2. Observed (points) and estimated (lines) counts of small (top) and large (bottom) Atlantic Salmon during dive surveys on the Middle River (left column), and Baddeck River (right column), NS, from 1983 to 2011, showing the productivity model fits to these data.

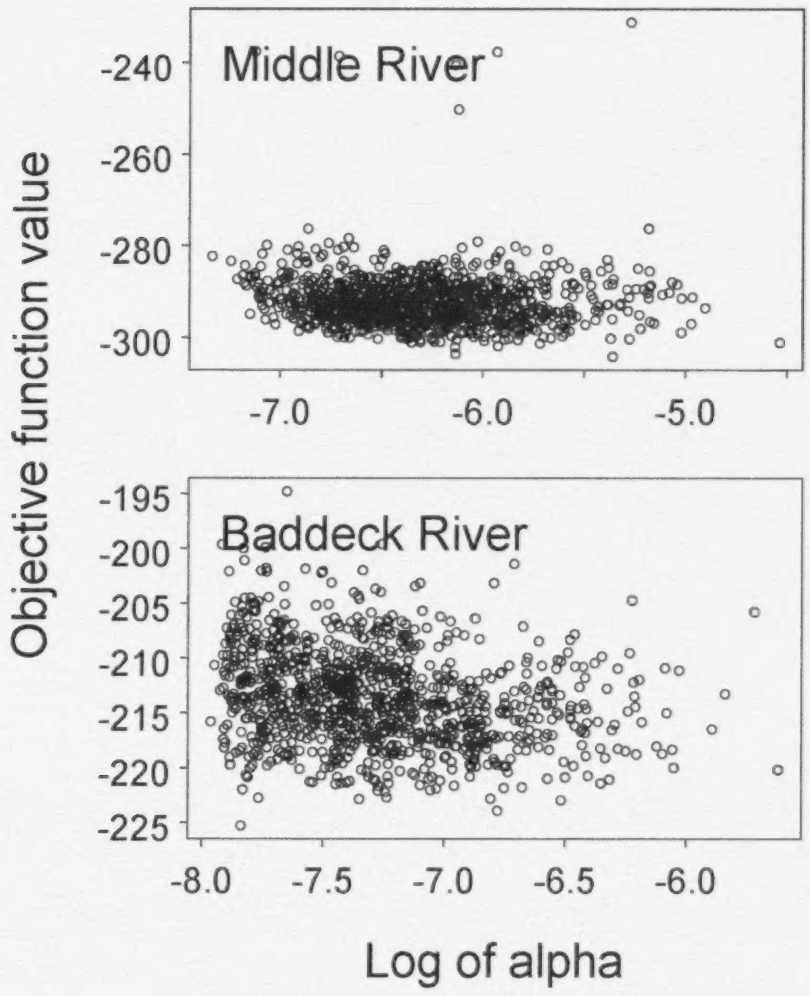

Figure 2.3. Comparison of the log of the slope at the origin of the stock recruitment relationship log(alpha) and the objective function value resulting from the MCMC runs of the productivity model for the Middle (top panel) and Baddeck (bottom panel) rivers.

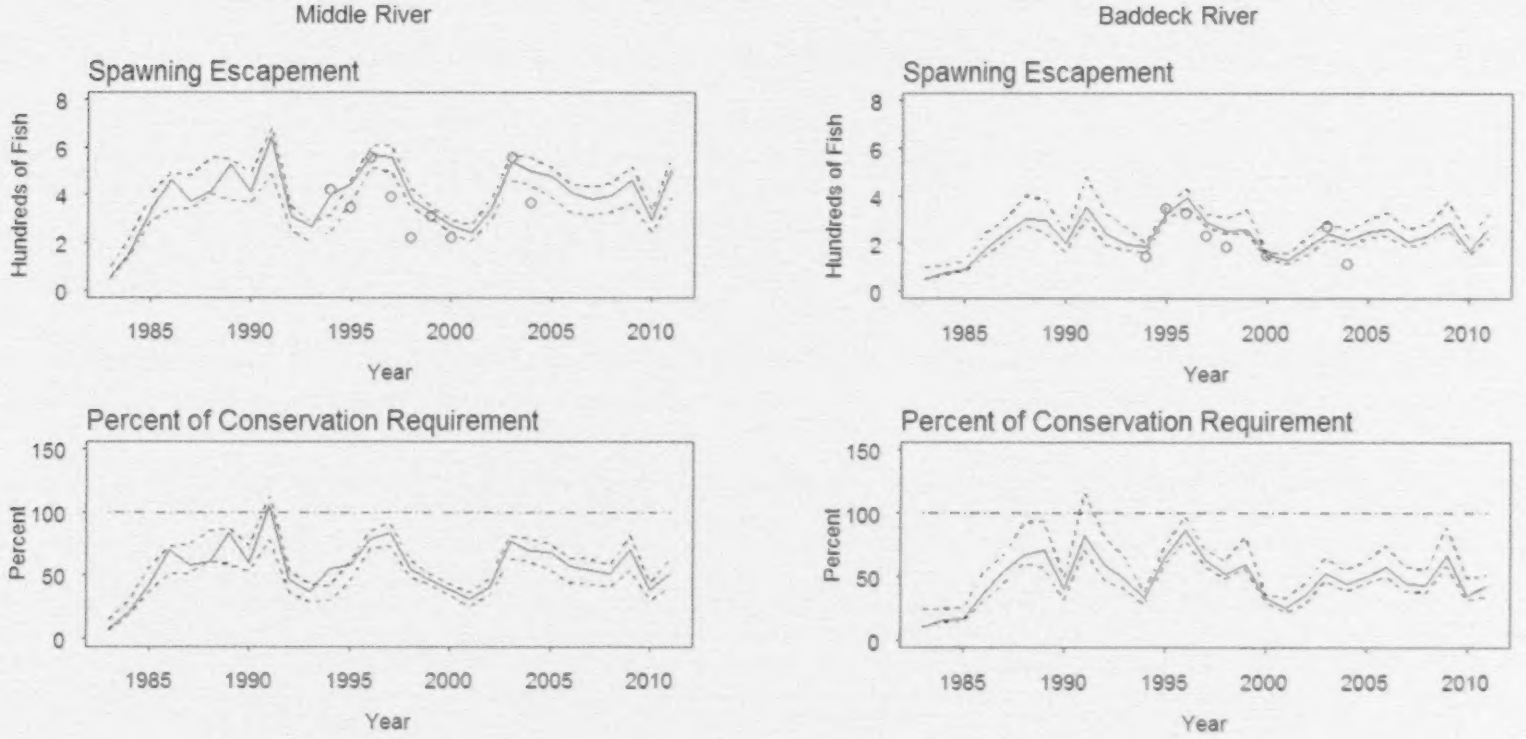

Figure 2.4. Estimated total number of spawners (top panels) and the percent of the conservation requirement attained (bottom panels) in Middle River (left column), and Baddeck River (right column), NS, from 1983 to 2011, as estimated with the productivity model. The solid lines are the estimated values and the dashed lines are the 10th and 90th percentiles of the posterior probability densities for the estimates (indicative of the uncertainty of the estimates). The points in the upper panel are the population estimates obtained by mark-recapture during the dive surveys. The horizontal dashed line in the bottom panel indicates 100% of the conservation requirement.

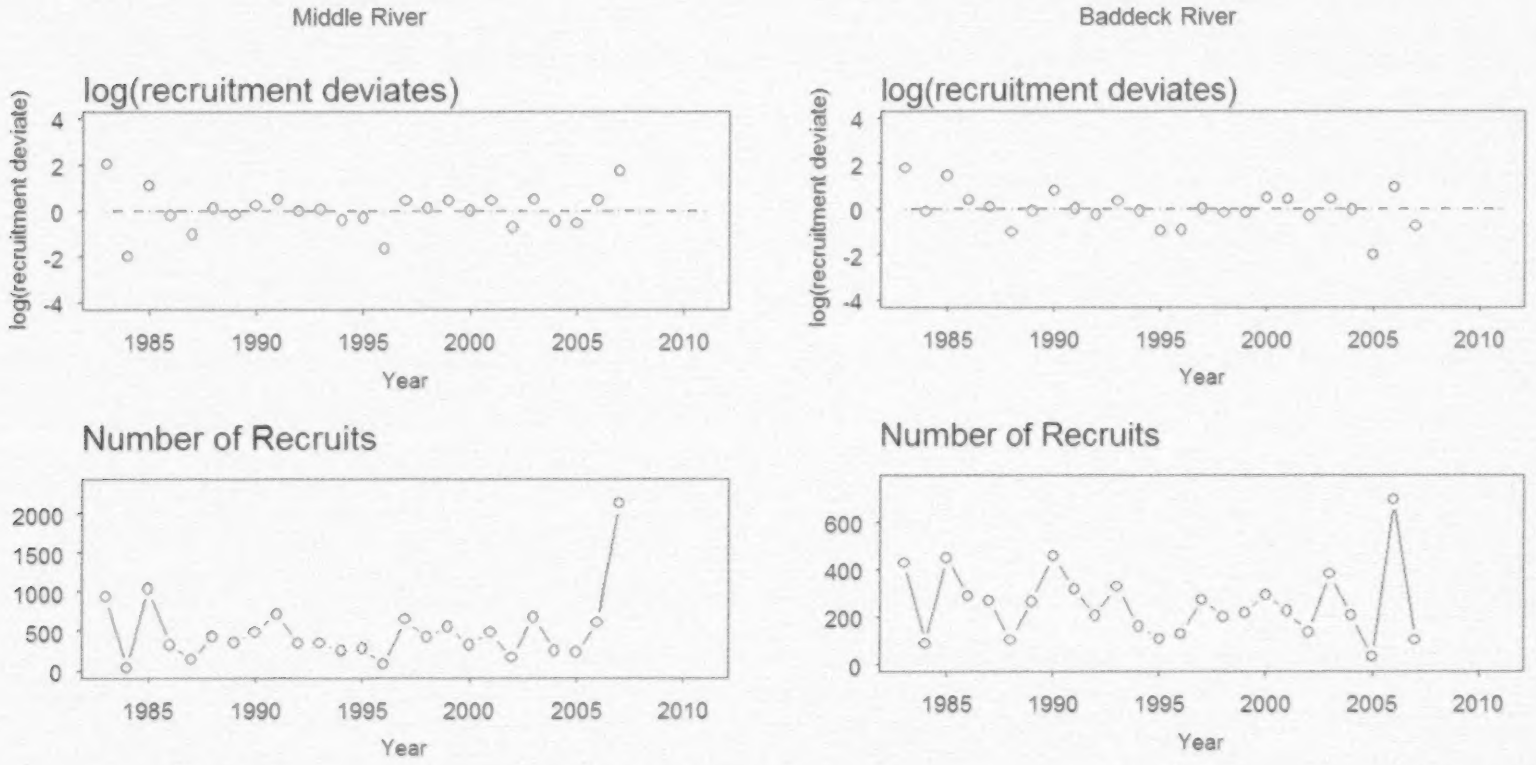

Figure 2.5. Estimated log-scale annual recruitment deviates (top panels) and estimated number of recruits produced annually by cohort year (bottom panels) for the Middle River (left column), and Baddeck River (right column) salmon populations from 1983 to 2007, as estimated with the productivity model.

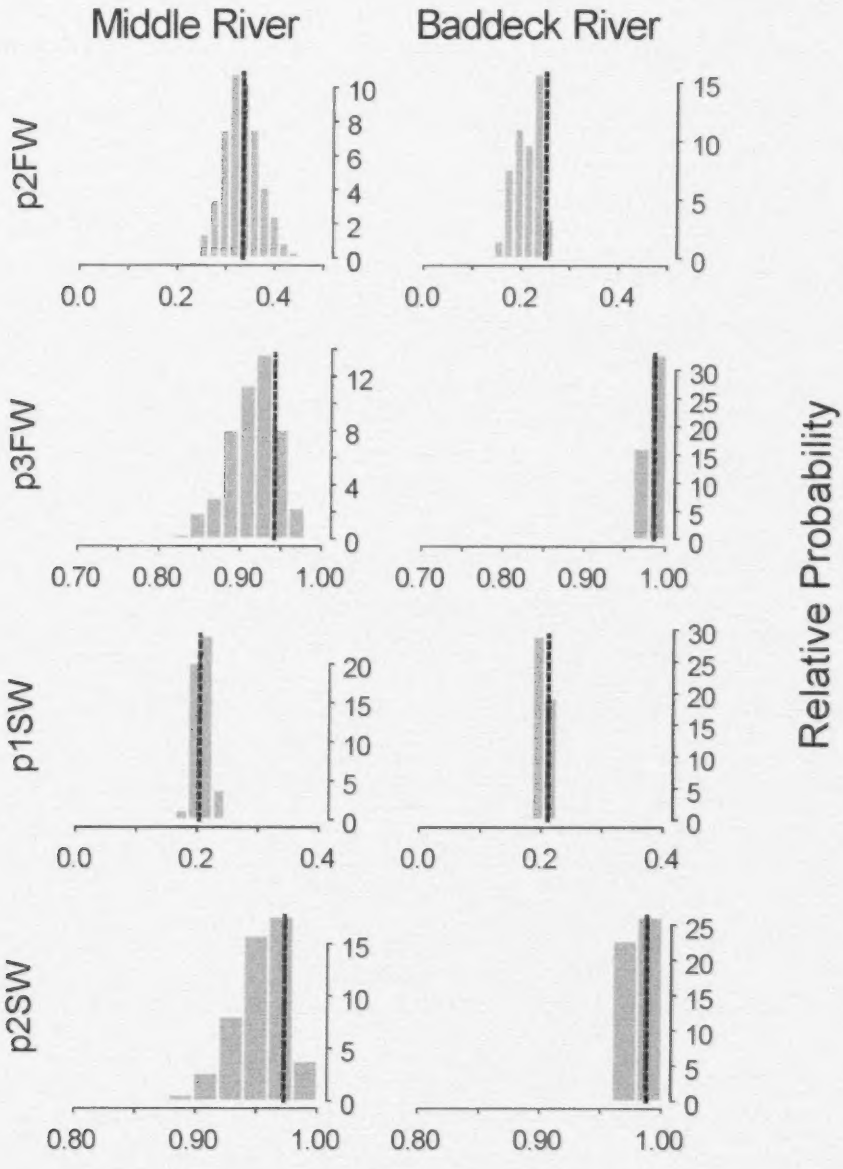

Figure 2.6. Bayesian posterior probability densities for the probabilities of undergoing smoltification at age-2 (p2FW), at age-3 (p3FW), of maturing after one winter at sea (p1SW) and after two winters at sea (p2SW) for Atlantic Salmon in the Middle River (left column) and Baddeck River (right column) as estimated with the productivity model. The vertical dashed lines show the maximum likelihood estimates from the model.

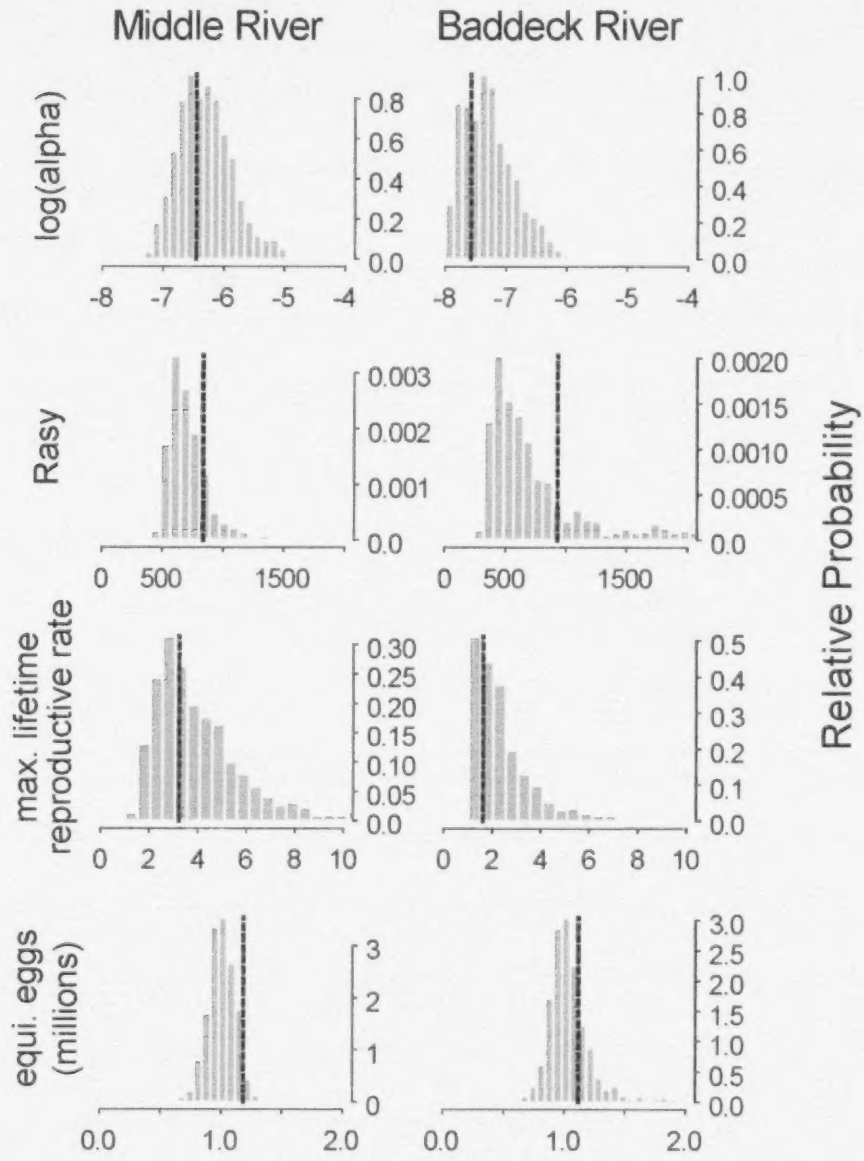

Figure 2.7. Bayesian posterior probability densities for the log of the maximum survivals from eggs to adults (log(alpha)), the asymptotic recruitment levels (Rasy, expressed as number of first time spawning adults), the maximum lifetime reproductive rates and the equilibrium egg depositions for Atlantic Salmon in the Middle River (left column) and Baddeck River (right column) as estimated with the productivity model. The vertical dashed lines show the maximum likelihood estimates from the model.

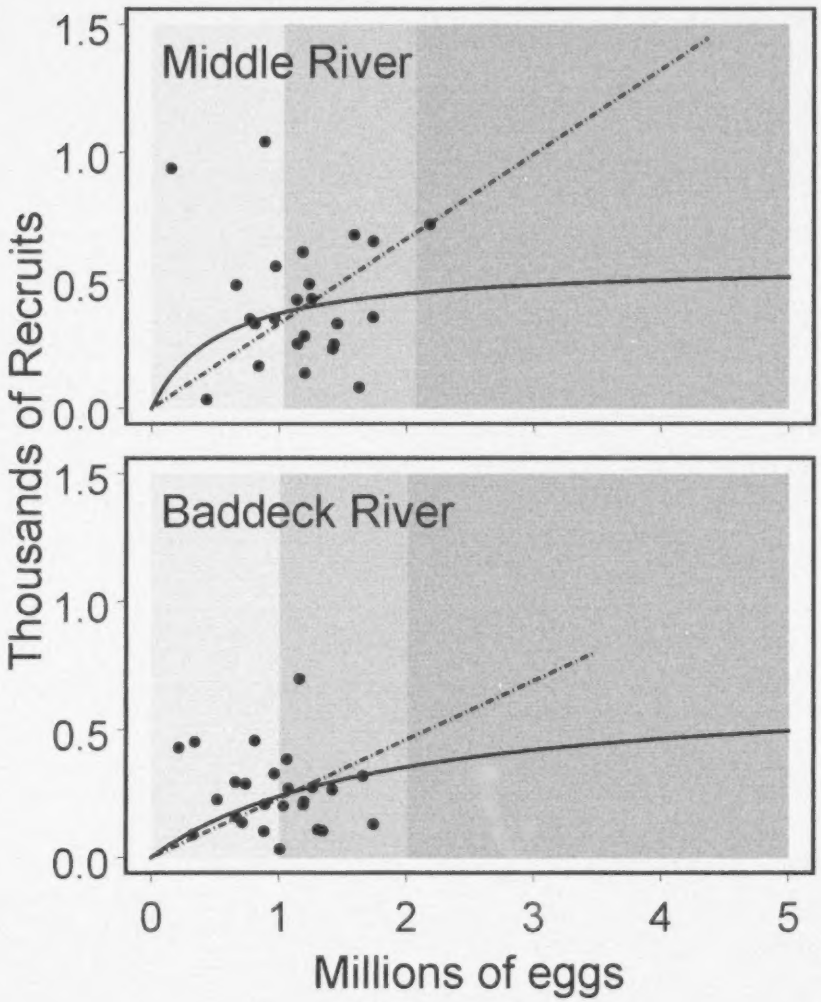

Figure 2.8. Equilibrium analysis of the dynamics of the Atlantic Salmon populations in the Middle (top) and Baddeck (bottom) rivers. The points are the estimated egg depositions and recruitment (total number of adults produced) for the 1983 to 2007 egg deposition years. The curved, solid lines are the stock recruitment relationships. The straight, dashed lines are the replacement lines that represent the lifetime egg production per recruit. Dark shading indicates egg depositions above the conservation [egg] requirement, medium shading is between 50% and 100% of the requirement, and the light shading is below 50% of the requirement.

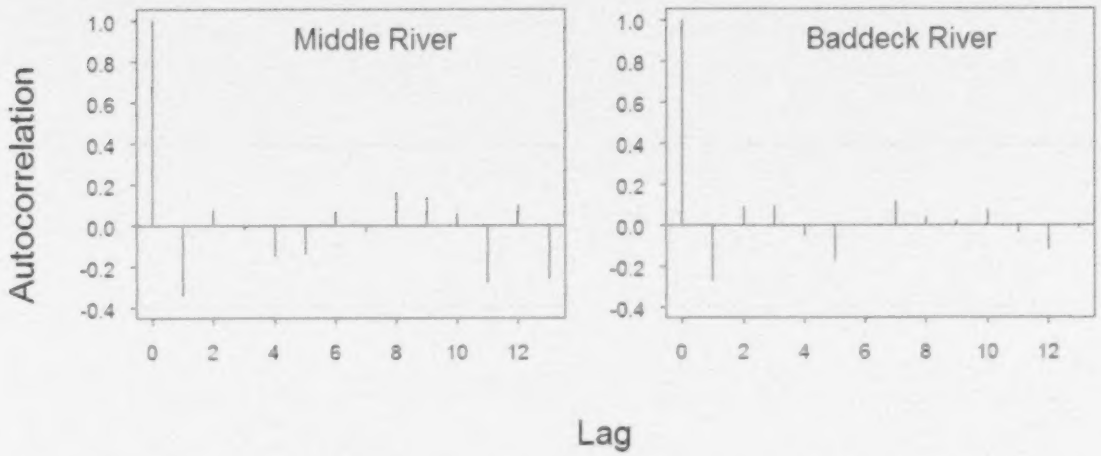

Figure 3.1. Autocorrelation coefficients in the log recruitment deviate time series for the Middle River (left) and Baddeck River (right) Atlantic Salmon populations at lags of zero to 15 years. The dashed lines indicate statistical significance at a 95% confidence level.

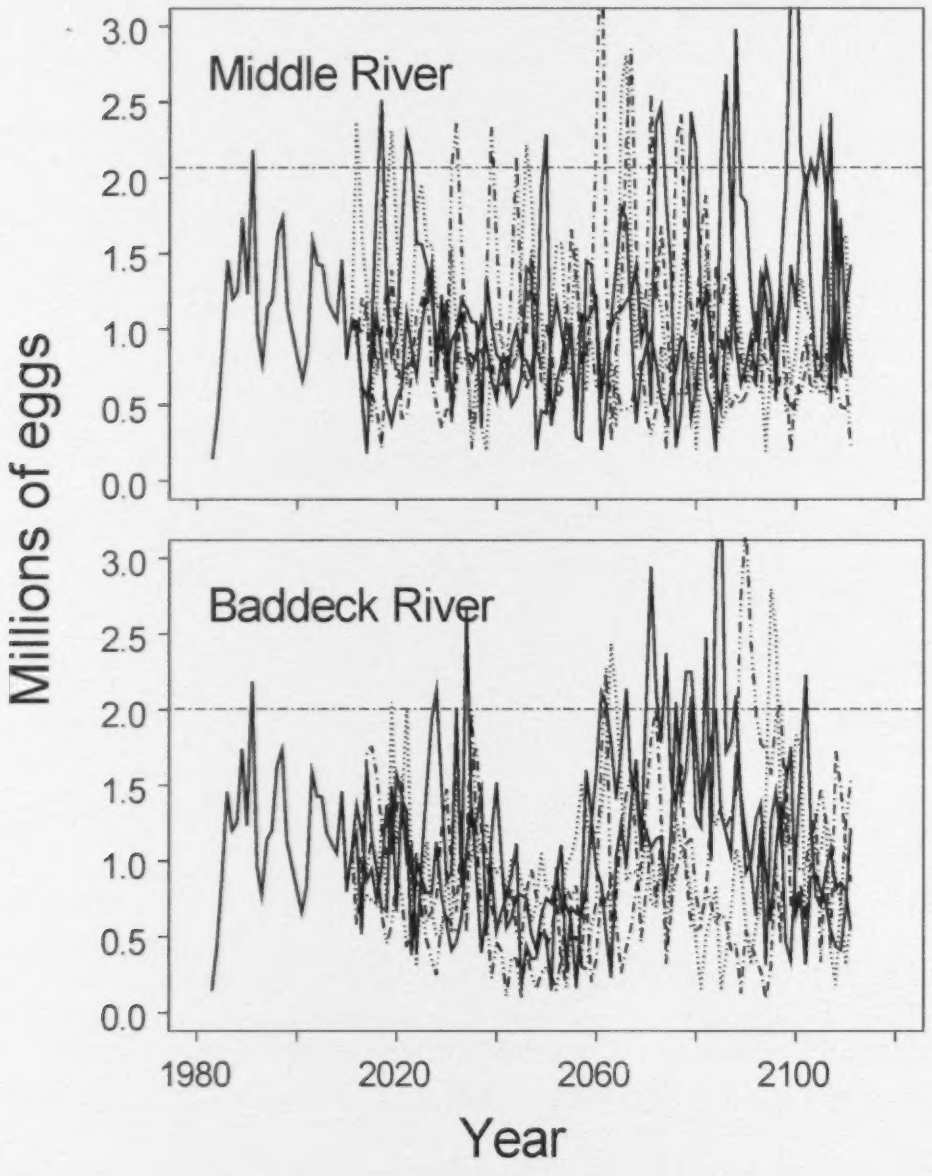

Figure 3.2. Examples of five simulated population trajectories from the Middle River (top) and Baddeck River (bottom) Atlantic Salmon population viability models using the base model dynamics representative of current conditions. Abundances from 1983 to 2011 are the annual abundance estimates obtained with the productivity model (see Section 2) and the solid, dotted and dashed lines show the simulation results for the next 100 years. The horizontal dashed line is the recovery target.

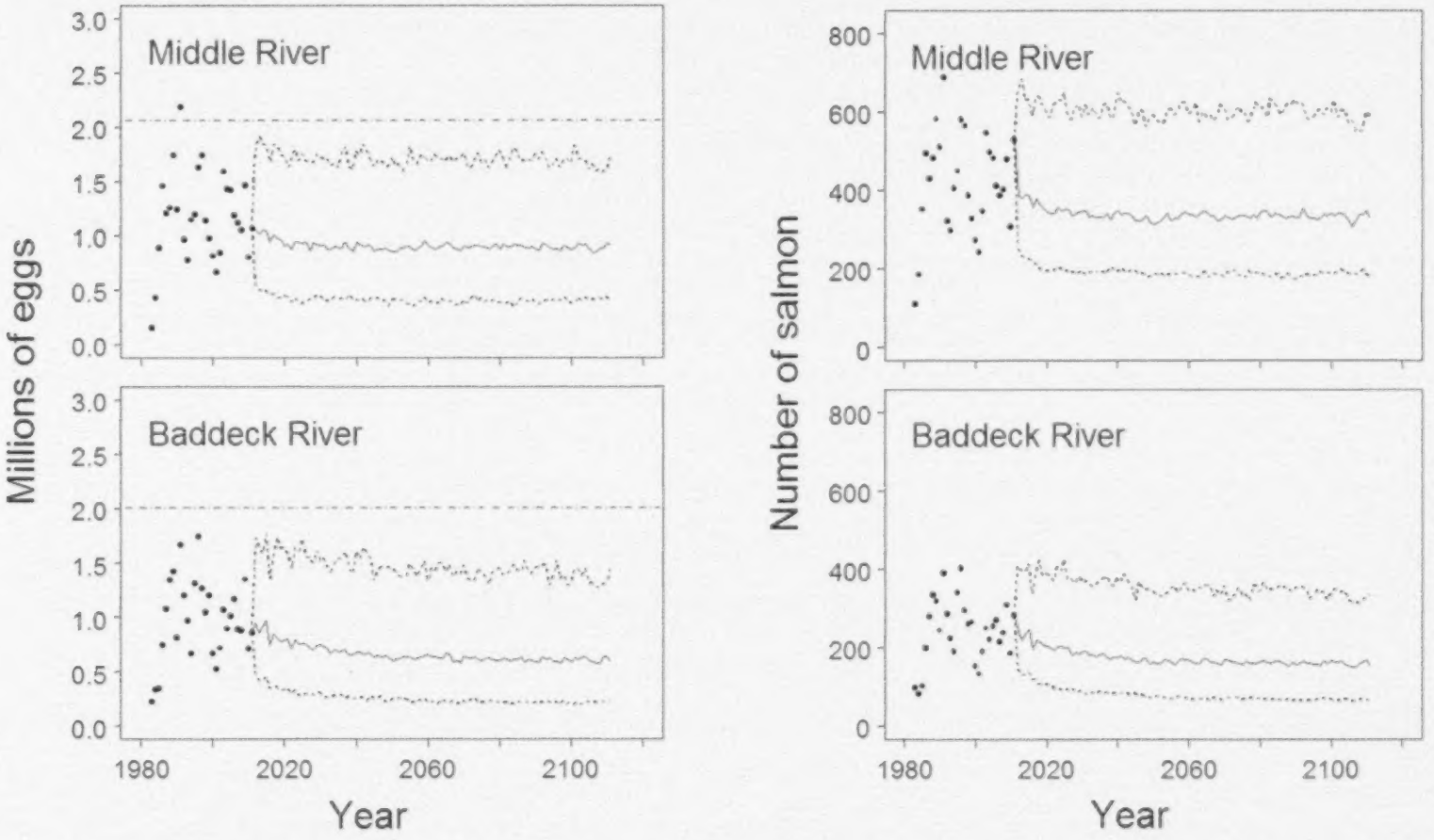

Figure 3.3. Simulated median abundance (solid line) with the 10th and 90th percentiles (dashed lines) for the egg (left column) and adult (right column) life stages from Monte Carlo simulations of the Middle River and Baddeck River Atlantic Salmon population viability models using the base model dynamics as representative of current conditions. The points show the annual abundance estimates obtained with the productivity model (see Section 2) from 1983 to 2011 and the lines show the simulation results for the next 100 years. The graphs summarize 1000 simulations for each population. The horizontal dashed line in the left panels is the recovery target.

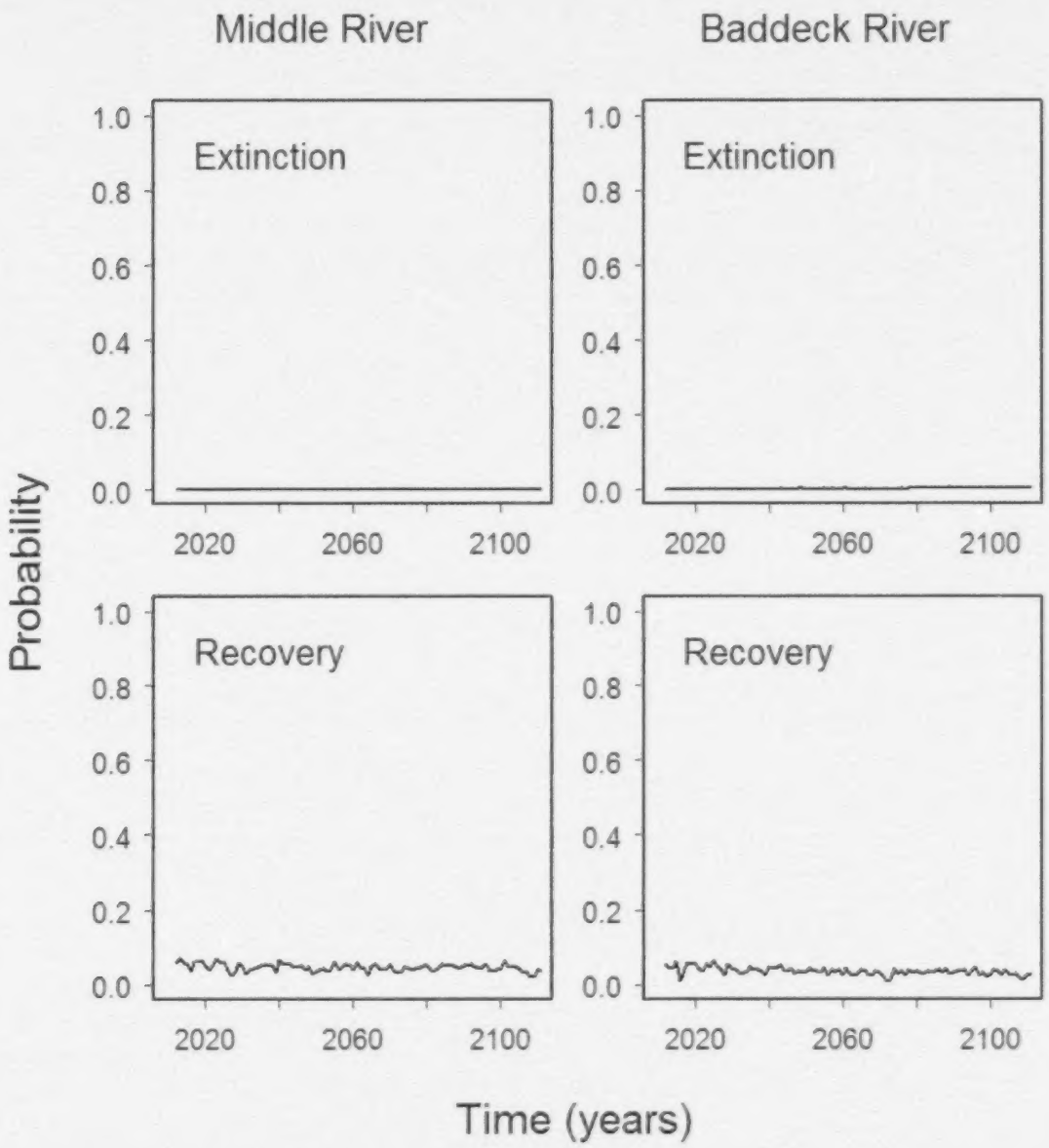

Figure 3.4. The probability of extinction (top row) and the probability of recovery (bottom row) from 2012 to 2111 for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations. Probabilities are calculated as the proportion of 1000 Monte Carlo simulations of population trajectories that either went extinct or met the recovery target.

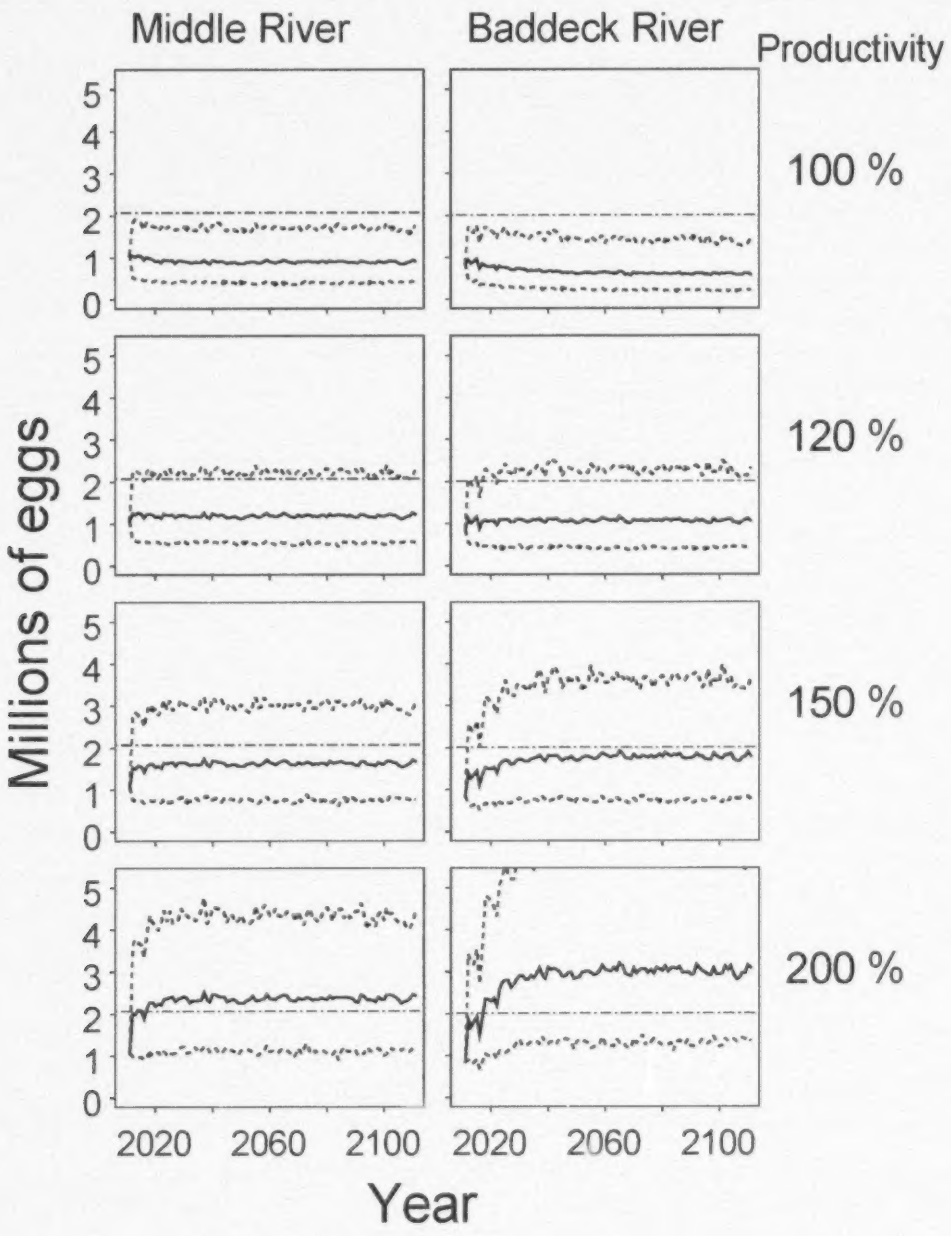

Figure 3.5. The effects of increasing productivity on the simulated abundance of eggs for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations from 2012 to 2111. The graphs summarize 1000 simulations for each scenario. The median abundance (solid line), and the 10th and 90th percentiles (dashed lines) are shown. The rows show the effect of increasing productivity by factors of 1 (no change), 1.2 (20% increase), 1.5 (50% increase) and 2.0 (100% increase).

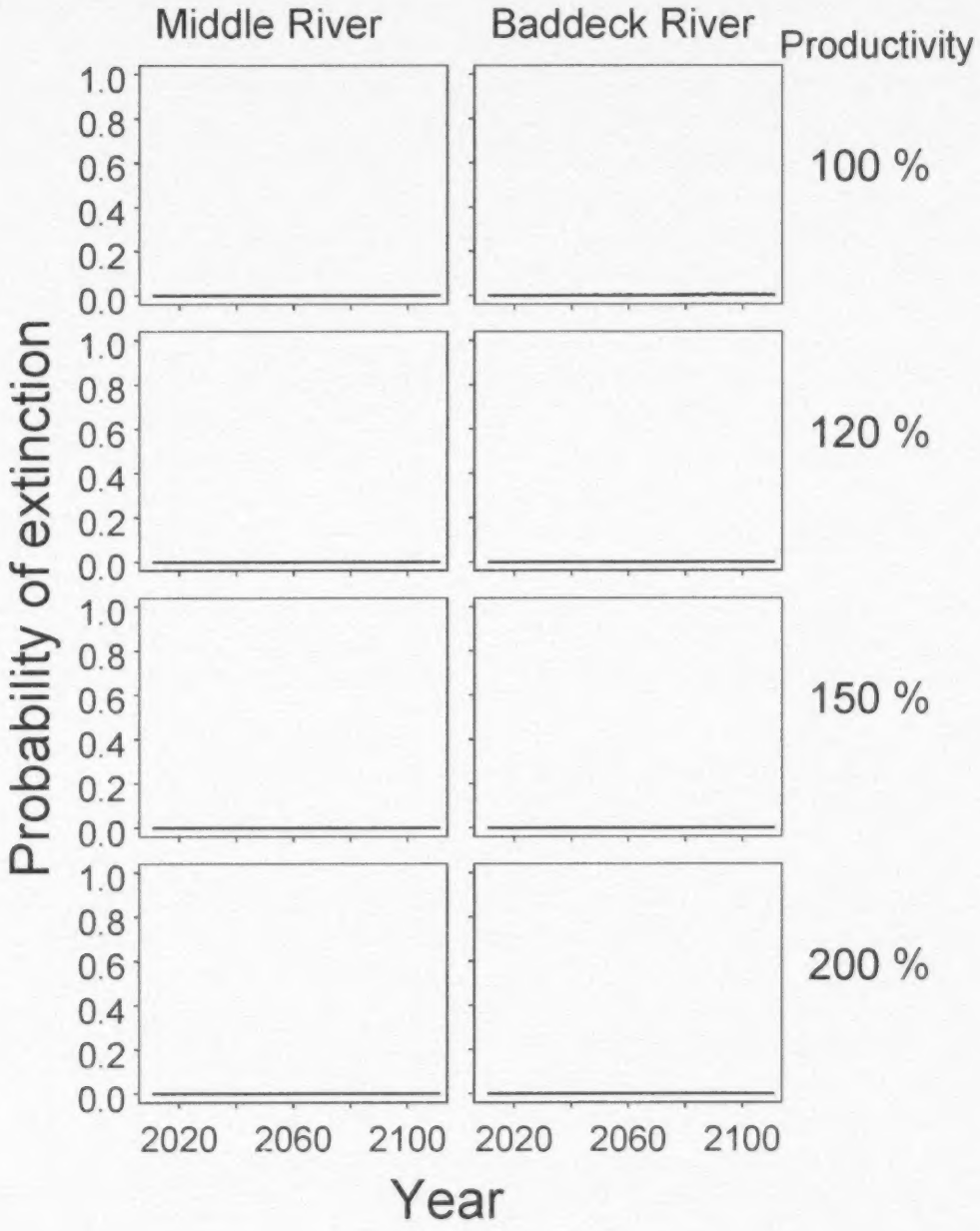

Figure 3.6. The effects of increasing at sea survival and freshwater productivity on the probability of extinction from 2012 to 2111 for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations. Panels are described in the caption for Figure 3.5.

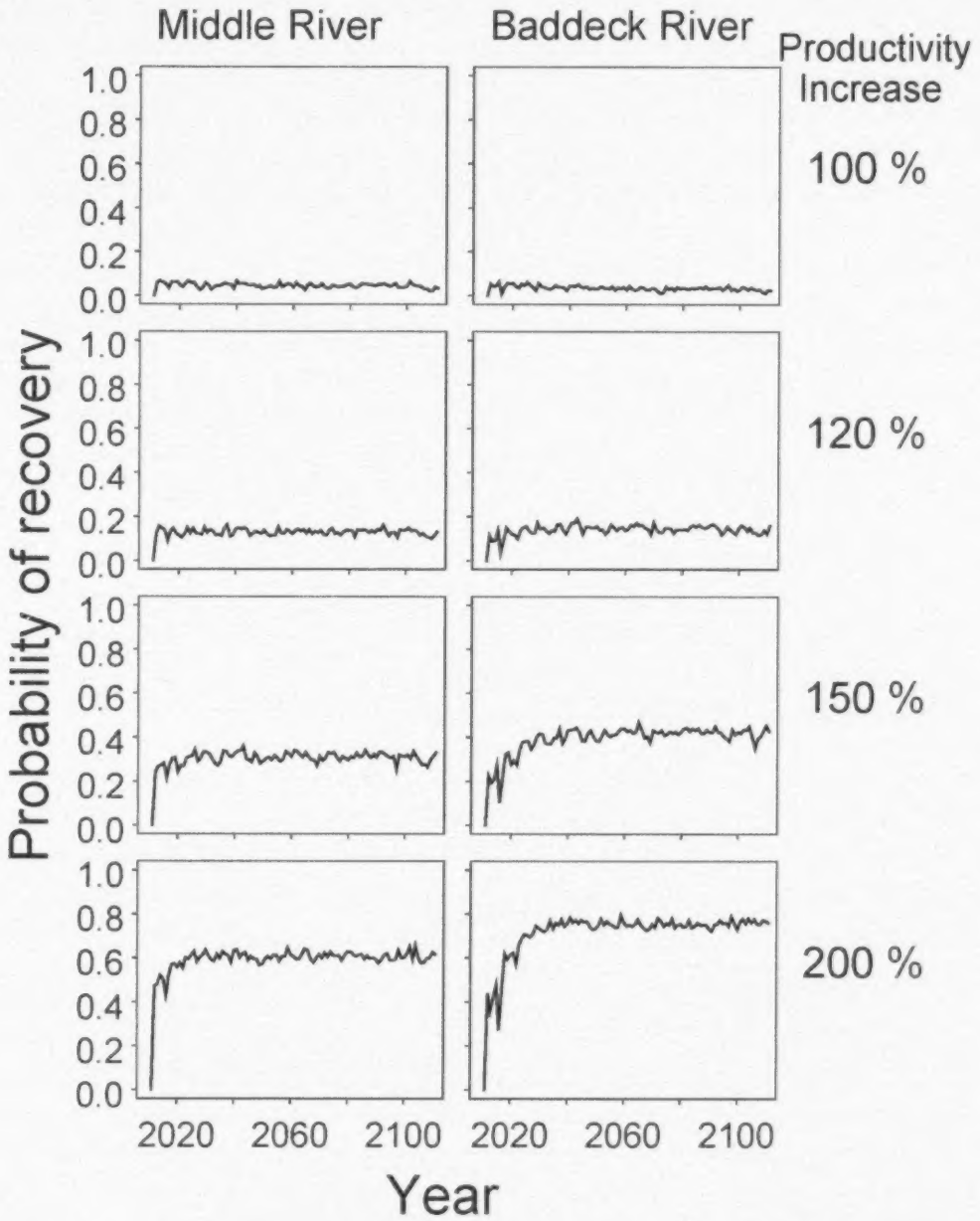

Figure 3.7. The effects of increasing at sea survival and freshwater productivity on the probability of recovery from 2012 to 2111 for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations. Panels are described in the caption for Figure 3.5.

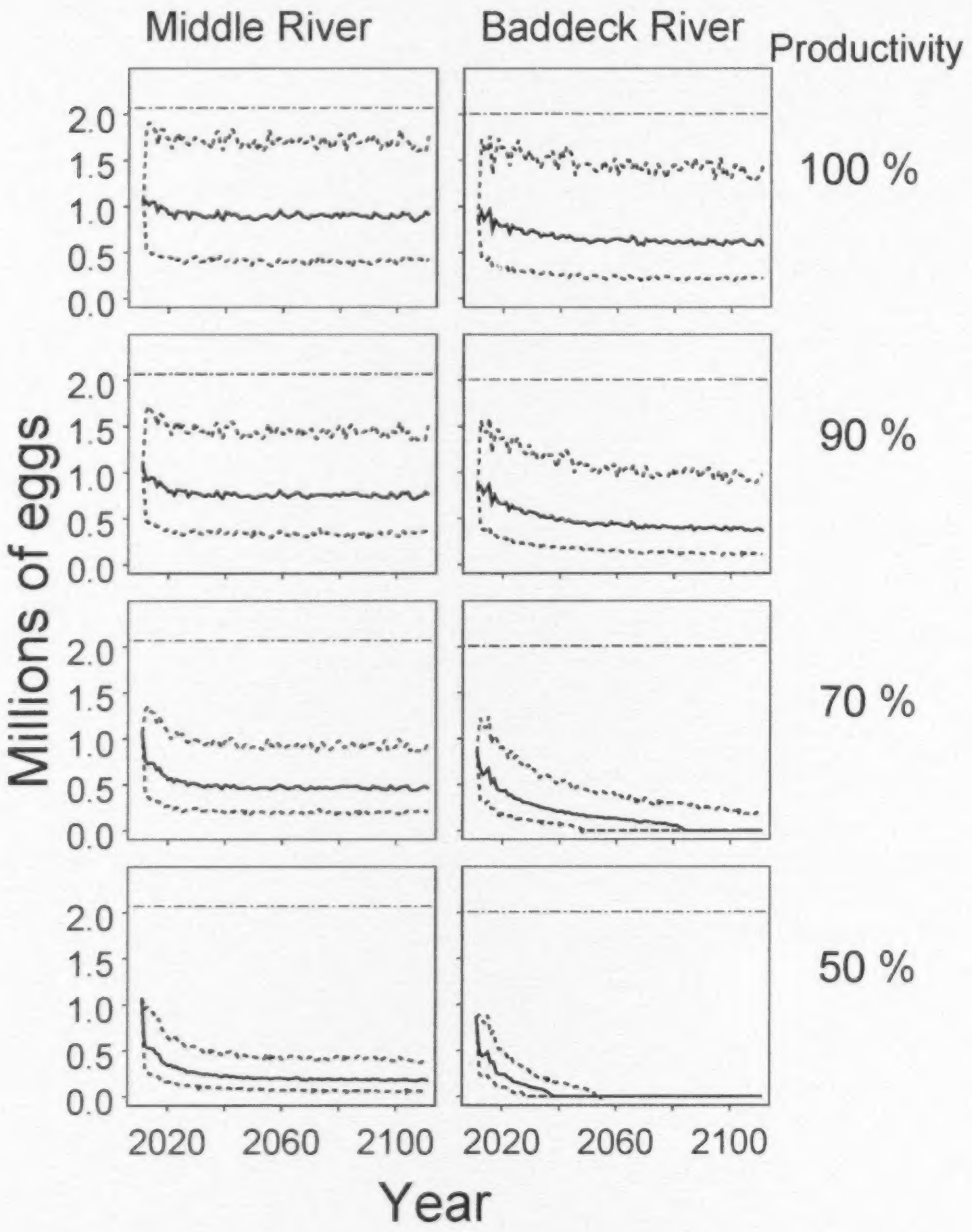

Figure 3.8. The effects of decreasing productivity on the simulated abundance of eggs from 2012 to 2111 for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations. The graphs summarize 1000 simulations for each scenario. The median abundance (solid line), and the 10th and 90th percentiles (dashed lines) are shown. The rows show the effect of decreasing productivity by factors of 1 (no change), 0.9, 0.7 and 0.5.

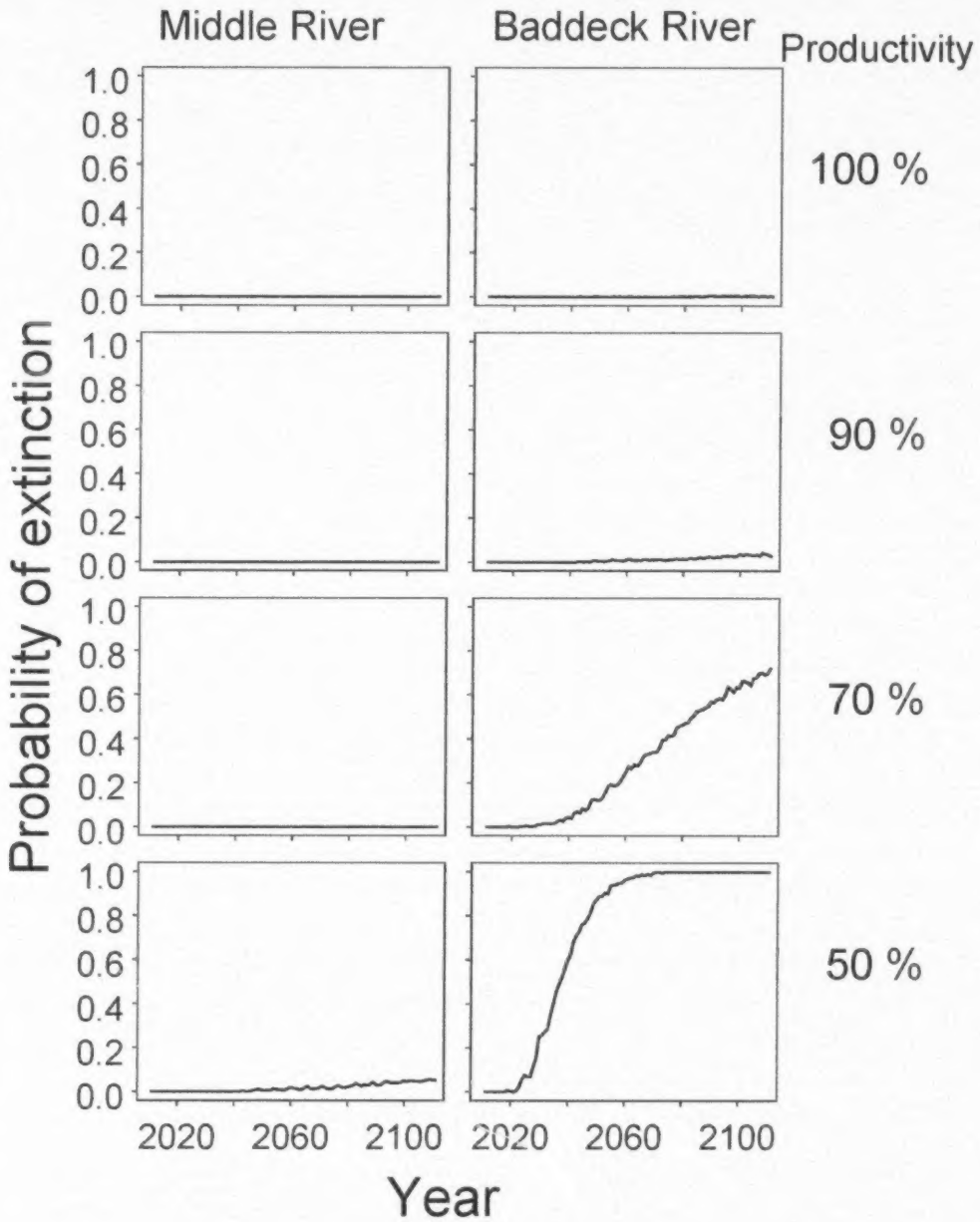

Figure 3.9. The effects of decreasing at sea survival and freshwater productivity on the probability of extinction from 2012 to 2111 for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations. Panels are described in the caption for Figure 3.8.

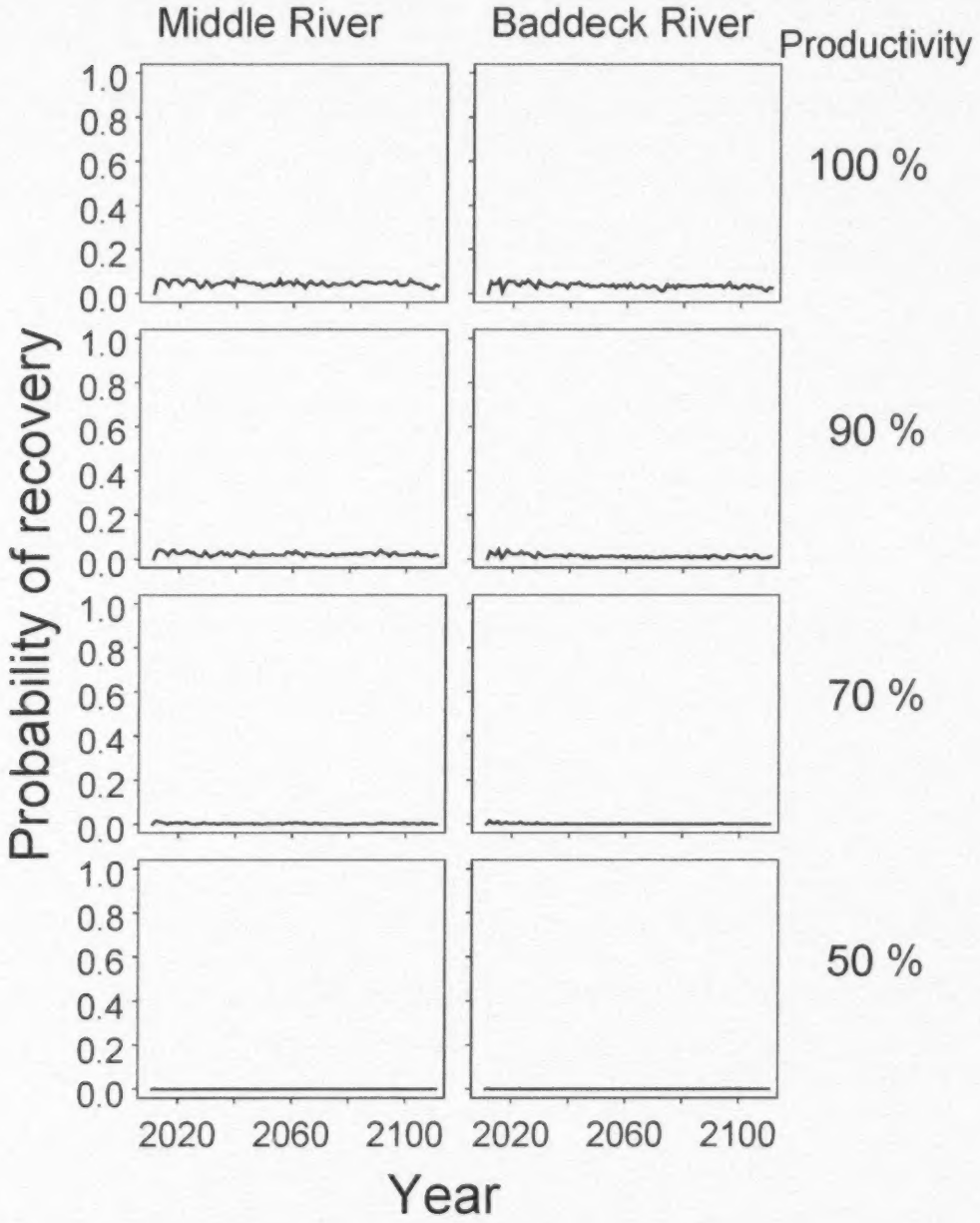

Figure 3.10. The effects of decreasing at sea survival and freshwater productivity on the probability of extinction from 2012 to 2111 for the Middle River (left column) and Baddeck River (right column) Atlantic Salmon populations. Panels are described in the caption for Figure 3.8.